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A Cost and Performance Comparison of Drainback and Integral Collector Storage Systems for Residential Domestic Hot Water

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SERI

PREFACE

Water heating and building space conditioning account for more than one third of the nation's total energy consumption. Because solar energy can be efficiently captured at the low to moderate temperatures required for space conditioning and water heating, there is a good match among the energy demand, resource, and technology. In support of the Federal Government's goals to encourage the provision of adequate, reliable, and reasonably priced energy supplies both today and over the long term, DOE's Active Heating and Cooling (AHAC) Program supports research to develop the technology base that will allow the private sector to produce competitive active solar products and services.

The AHAC program consists of research on systems, components, and materials for solar cooling, heating, and domestic hot water applications. The technologies being pursued include heating, closed- and open-cycle absorption cooling, and liquid and solid desiccant cooling. The systems research associated with the AHAC program consists of analysis, experimental testing, and reliability testing and evaluation.

The systems analysis subelement consists of developing, validating, and exercising algorithms that model advanced active heating and cooling systems and their control strategies. Where analytical tools do not exist or are inadequate for assessing the performance of new system concepts, algorithms are developed and validated analytically or empirically or both. System performance is analyzed to compare alternative operation strategies, designs, component and material opportunities, and research priorities. When new algorithms are created and validated, they are made available through the TRNSYS library and, where appropriate, converted to the F-CHART design method.

The goals of the reliability research subelement are to identify the causes and frequency of AHAC systems reliability problems and to recommend and perform appropriate research to improve the overall reliability of AHAC systems. Specific activities include testing component reliability in the laboratory, testing materials and components outdoors, developing test standards for critical components, developing and applying analysis techniques to estimate how reliability affects system performance and delivered energy cost, and evaluating the performance of state-of-the-art AHAC systems.

The systems testing subelement is composed of laboratory and field evaluation of both state-of-the-art and advanced active systems concepts. The systems tests generate data that can be used to validate system-level models, verify operation strategies, and identify opportunities for improved control strategies and problem solving in component, material, and system design and operation. Testing systems in highly controlled and instrumented situations allows the researcher to benchmark the performance and sensitivity of the system to the important driving functions (e.g., load, insolation, weather, control strategy).

The systems research subelement identifies (through analysis and testing) problems and opportunities with materials and components in which research is required to develop reliable systems that minimize the cost of delivered energy.

This report supports the systems research program by presenting analytical tools for predicting the performance of integral collector storage (ICS) systems in short-term Solar Rating and Certification Corporation (SRCC) system tests and annually. Additionally, an economic analysis of ICS and drainback systems, based on consistent cost estimates, provides a comparative means to evaluate these two systems.

This report describes the work performed under the FY 1984 SERI Task No. 3002.30, "Solar Space and Hot Water Heating Systems Analysis." The authors would like to express their appreciation to the following individuals who provided valuable comments during the review of the document: John Biemer of the Bonneville Power Administration, Doug Cornell of Cornell Energy Systems, Sandy Klein of the University of Wisconsin-Madison, Jay McLaughlin of Servamatic Systems, Dave Robison of the Oregon Department of Energy, Bill Thomas of Virginia Polytechnic and State University, Rich Wipfler of FAFCO, and Rob Farrington, Larry Flowers, and Walter Short of SERI.

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SUMMARY

Objective

The objective is to examine new solar domestic hot water (SDHW)/space heating systems that have the potential for reduced cost, improved performance, or both.

Discussion

This report describes the work done in FY 1984 in the Solar Energy Research Institute's (SERI's) continuing effort to identify low-cost systems for domestic hot water and space heating applications that can significantly improve the delivered energy cost of these systems. We chose to concentrate our efforts in this work on domestic hot water applications.

In earlier SERI work the advantages of drainback systems for the DHW application have been identified. It appears that drainback systems have the potential for incorporating low-cost components in a more cost-effective and reliable system. In this report we have provided updated cost estimates for three drainback systems: a commercially available system using currently available hardware, and two lower-cost systems using available low-cost collectors and low-cost components. We used F-CHART to predict the performance of these drainback systems so that an overall estimate of their economics could be obtained.

While there appears to be much promise for low-cost drainback systems, we also identified other systems that have the potential for low delivered energy costs. We chose to study the integral collector/storage (ICS) system in this work because these systems are rapidly increasing in consumer sales and relatively little analytical work was available with which to evaluate their performance.

In studying the ICS system, we reviewed the various configurations and determined that the two most common designs were the multiple tank and the single tank with reflector. These two designs have somewhat different performance characteristics. The multiple-tank design has a somewhat larger surface area for heat loss but has better optical performance than the single tank with reflector. We surveyed ICS system manufacturers to determine the range of costs involved with design, manufacturing, and marketing of the systems in the market today. Costs from this survey were used to provide an overall installed cost estimate for an ICS system. The same costing approach was used for this exercise as for the drainback system costs.

During the course of this work, a methodology for predicting the long-term performance of ICS systems was developed at the University of Wisconsin. We used this methodology to predict the annual performance of the same ICS system for which costs were developed. At the same time, a simple model for ICS performance was developed and applied to predict the performance of ICS systems in the Solar Rating and Certification Corporation (SRCC) 200-82 test standard. Taking design data for ICS units that had already been tested under this

standard, we attempted to determine the simple model parameters that could predict the SRCC test results. These parameters, which are basically the same as those for the long-term methodology, can then be used to predict long-term performance.

With both cost and performance data for ICS and drainback systems, an economic analysis was then conducted. We chose to use discounted payback as the figure of merit for economics. This was done to be consistent with previous SERI studies and because of its relative simplicity. In addition to the initial, installed cost of the systems, a life-cycle cost for repairs and replacements was estimated based on some recent work in this area at SERI.

Conclusions

Low-cost versions of drainback systems have the potential to reduce installed costs by almost 40% over optimistically priced, commercially available systems. If a durable, low-cost, high-performance collector could be developed, payback periods of slightly under 10 years (versus electricity) would be possible without tax credits. Further cost reductions would require the development of other innovative system concepts.

ICS systems were studied as an alternative to drainback systems for heating domestic water (but not for space heating). Their attraction lies in their simplicity; namely, no pump or controller is required, and the entire system comes in one package. Two basic ICS system designs were studied: a single tank with reflector and a multiple tank configuration. Two computer models were developed. One simulates an SRCC-82 system test and allows for ICS model parameters to be determined from published SRCC test results. A second model takes these parameters and, using a methodology developed at the University of Wisconsin, predicts annual performance.

The ICS simulation results indicate that attempts to reduce overnight losses by lowering the loss coefficient can unfortunately be offset by even small corresponding reductions in optical efficiency. In comparing the two ICS system types (single versus multiple tank), the single tank system has lower heat losses due to a smaller tank area, but a lower optical efficiency due to the presence of the reflector. In terms of annual performance, neither system design emerged as a clear winner, although additional concentration is possible with the single tank design (at an added cost).

The optimum tank volume (system capacitance) was found to be dependent on draw profile. For a continuous draw, performance at any given aperture area is completely independent of tank volume. (If the energy balance equation for a constant draw is integrated over time, the storage mass appears only in the tank internal energy term, and this term can be considered negligible over long periods such as a month.) Draw profiles characterized by an average draw temperature less than the average tank temperature (e.g., night draw) benefit from larger tanks, which have a smaller diurnal temperature variation. Conversely, a draw profile weighted to the daytime would do better with smaller tank sizes (although as with other active systems, if the tank is too small, collector efficiency suffers during nondraw conditions). A complete study of this issue was not attempted.

A survey of ICS manufacturers revealed that system costs per unit area are only slightly less than those of other active systems on the market. Compared to flat-plate collectors, ICS units are considerably more expensive per unit area. While the overall cost for a typical ICS system may be less than for a typical drainback system (e.g., comparing the ICS to the commercial drainback), the ICS system does not deliver as much energy. An economic comparison showed that the ICS system has a shorter payback than the commercial drainback system and about the same payback as the low-cost drainback system. It must be pointed out that the low-cost drainback system has not been tested or commercially developed and that the costs estimated for the ICS system were taken from the optimistic end of the cost range from the manufacturers' survey.

If a high-performance, low-cost, flat-plate collector could be developed with a system cost similar to the low-cost system evaluated in this report but with the performance of the commercial system, then the overall economics are improved considerably.

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NOMENCLATURE

A	$(1 + G)/(1 + R)$
A_c	collection area of the ICS system (m^2)
B_0	incident angle modifier coefficient
c_p	specific heat of water (kJ/kg°C)
C	system cost ($)
D	tank diameter (m)
$f_{m,c}$	solar fraction for the fully mixed tank
f_{DHW}	solar fraction
F	first year fuel savings ($)
$F_R U_L$	heat loss coefficient (W/m^2 °C)
g	gravitational constant (9.8 m/s^2)
G	fuel escalation rate
h_f	heat transfer coefficient (W/m^2 °C)
H_T	daily average incident radiation in the plane of the glazing (kJ/m^2 day)
k	thermal conductivity (W/m°C)
L	tank length (m)
ℓ	heat loss coefficient (W/m^2 °C)
$\dot{m}c_p$	load flow capacity (W/°C)
Mc_p	system heat capacity (J/°C)
M_D	mass of water withdrawn for the load during the month (kg)
n	number of days in the month
N	number of nodes
P	discounted payback period (yr)
Q_{del}	delivered energy (kJ)
Q_{inc}	incident solar energy in aperture plane (W)
Q_{loss}	lost energy (kJ)
Q_s	absorbed solar energy (W)
Q_u	useful energy delivered (kJ)
Q_{AUX}	auxiliary energy consumption (kJ)
Q_{CAP}	auxiliary energy capacity (kJ)
Q_{DL}	standard test load (kJ)
Q_{NET}	solar energy delivered (kJ)

NOMENCLATURE (Continued)

Q_{PAR}	parasitic energy consumption (kJ)
Q_{RES}	reserve energy capacity (kJ)
R	discount rate
S	optimum ratio of storage volume to collector area (m^3/m^2)
t	time (s)
T	tank temperature (^oC)
T_a	ambient temperature (^oC)
T_{in}	fluid inlet temperature (^oC)
$\overline{T}_a$	monthly ambient temperature (^oC)
$\overline{T}_e$	effective sink temperature (^oC)
$\overline{T}_m$	mains water temperature (^oC)
$\overline{T}_t$	average tank temperature (^oC)
$\overline{T}_D$	average draw temperature (^oC)
U	overall loss coefficient ($W/m^2\ ^oC$)
UA	overall loss coefficient ($W/^oC$)
U_L	loss coefficient ($W/m^2\ ^oC$)
W	reflector width (m)
ΔT	temperature differential (^oC)
$\Delta\theta$	amount of time in the month (s)
η_o	normal transmittance-absorptance product
$\overline{\eta}_o$	average monthly optical efficiency
θ	incident angle
ρ	density (kg/m^3)

SECTION 1.0

INTRODUCTION

1.1 BACKGROUND

Residential and commercial building space conditioning and water heating account for more than a third of the nation's total energy consumption (SERI 1981) and therefore represent a significant target for energy displacement. The development of solar technology for active space conditioning and hot water systems has progressed to the point that, with the financial aid of tax credits, there are a significant number of commercial and residential systems in operation.

As stated in the National Active Solar Heating and Cooling (AHAC) Program Five Year Research Plan (1985):

> The Federal Government has established a goal in the area of energy to encourage the provision, both today and over the long-term future, of adequate, reliable and reasonably priced energy supplies. The role of the Federal Government in achieving this goal is primarily one of fostering a technical and economic environment that encourages private initiative and promotes efficient use of the nation's energy and economic resources. The Active Solar Heating and Cooling Program is primarily concerned with research and development to establish viability and readiness for the commercial market. Specifically, this is expected to contribute a significant share of energy supplies for building applications.

The current viability of commercially available active heating and hot water systems is largely a result of substantial federal and state income tax credits. Without tax credits, there is little hope for significant energy displacement with current technology and cost. To achieve greater market acceptance of active solar systems, industry and government are pursuing the development of systems that will substantially reduce delivered energy cost. Considerable effort in research, development, and production of low-cost solar domestic hot water (SDHW)/space heating hardware has already been conducted with some success. For example, several manufacturers have developed a production capability for collectors that sell at $\$75/m^2$ ($\$7/ft^2$) to distributors and dealers. However, the state of the art is far from economically competitive and there is a need for continued research to formulate, analyze, and test innovative approaches, concepts, techniques, and hardware that have the potential for substantially reducing delivered energy costs. Clearly, incremental improvements in delivered energy costs will not be enough to achieve the goal of economic viability.

From 1981 to 1983, SERI undertook a study to develop low-cost collectors and systems that identified many new ideas with good potential to significantly reduce system cost (Kutscher et al. 1984). A primary conclusion of this work was that the greatest potential cost reductions for pumped systems are possible with a drainback liquid DHW/space heating system. Few valves are required and no automatic valves, which are prone to failure, are necessary. According to a comparison by Argonne National Laboratory (1981), drainback systems have approximately a 40% greater mean time between failures than do drainout systems. It is the relatively simple design of drainback systems that increases overall reliability. Freeze protection is fail-safe as long as proper installation techniques are employed. Water can be used as the working fluid with its inherent advantages. If load-side heat exchangers are employed, then low-cost collectors and unpressurized storage tanks can be used. This last item provides the low-cost potential of the drainback system. Use of low-cost collectors, plastic pipe, and low-cost storage could significantly reduce current installed system costs of over $540/m^2$ ($50/ft^2$). However, if tax credits are disallowed, the study concluded that installed costs must drop to $110/m^2$ ($10/ft^2$) to provide a 40% market penetration for residential all-electricity customers. This corresponds to a five-year payback based on the performance assumptions in the study.

Although drainback systems have been investigated in some detail at SERI, and many installers in the field have gained experience with them, several research issues still remain to be resolved before drainback systems move completely out of the scope of AHAC program work. These primarily include component-related issues such as optimum design of collector-side and load-side heat exchangers; performance of polybutylene pipe under actual conditions; pressure limitations in unvented, closed-loop drainback systems; corrosion in vented, closed-loop systems; evaporation in vented systems; effect of boiling and subsequent increased pressure when filling a hot, stagnated collector; and performance of a pumped loop between the solar and auxiliary tanks (in two-tank systems). Although the resolution of these issues will result in better performing, more reliable drainback systems, cost remains a barrier to large market penetration.

The Active Program Research Requirements (APRR) study (Scholten and Morehouse 1983) drew a similar conclusion, although in a different form. It shows that residential liquid heating/hot water systems have optimistic cost-to-cost-goal ratios in excess of 2:1. Additionally, significant real fuel escalation rates are required if these systems are to become competitive by the year 2000. Of the 12 systems ranked, liquid heating systems, including drainback, received the highest evaluation in the APRR study of all residential systems. The need for new ideas and projects was also specifically identified in the APRR study, as many system concepts were not included in the process because of a lack of available information and analytical models. It is therefore important to address innovative concepts and systems that have the potential for large cost advantages over currently available active systems.

An ideal innovative system that would solve the economic barriers would have the following characteristics:

- Reliability
- Few components
- Simple installation
- Potential for mass production
- Low installed or life-cycle cost

- No parasitic power requirements
- Efficiency comparable to drainback systems.

Our survey of possible systems identified the integral collector/storage (ICS) system as meeting many of these criteria (for DHW-only applications), including few components (a tank, a glazed box, and plumbing); simple installation (nominally, roof mounting with pipes to the mains and the conventional water heater); potential for mass production (the integral nature of ICS systems lends itself to mass production); and no parasitic power requirement (no pump). Current costs of ICS systems vary widely, but there is a potential for systems to be very cheap if they are mass-produced and if installation procedures are streamlined.

ICS systems are new in the market compared with other domestic water heating technologies. Analytical tools for predicting both instantaneous and annual performance are scarce. While ICS systems are becoming more common in the marketplace, a large variation in installed costs exists, which makes straightforward comparisons difficult without further evaluation.

Other systems may also meet the criteria for lowering delivered energy costs for domestic hot water applications. These include the many variations on the thermosiphon system: unitary (both with and without a boiling working fluid) and the more traditional system with separate components.

1.2 OBJECTIVE

Because funds and personnel were limited, we chose to focus our attention on the comparison between drainback and ICS systems. Since ICS systems appear to have potential for greater cost-effectiveness than drainback systems, the primary objective of our present work has been to review and update the performance and cost data for drainback systems and to assess the performance and cost potential of ICS systems. This information will then be used to compare, using the same criteria, drainback and ICS system cost-effectiveness.

1.3 APPROACH

The approach to accomplishing the stated objective has been to review the available literature on ICS performance models, develop a modeling capability, exercise the models to generate performance data, review existing ICS designs, and establish a consistent cost basis. We have developed a modeling capability, beginning with relatively simple models. Although two detailed models of specific ICS designs are available, they had limited utility in our present work. A simple ICS model was used to predict performance in an industry standard systems test. Test data from the systems test were compared with the predictions in order to partially validate the simple model. The model parameters were then used in an annual performance prediction methodology (available in the published literature) to generate long-term performance estimates for the ICS designs modeled. A more thorough validation is necessary if we are to be completely confident that a simple model can predict long-term performance adequately. To assess existing designs, we received in detail the current systems in terms of design, cost, and marketing strategy. A survey of all current manufacturers was conducted to obtain this information. The cost data were then used to generate an installed-cost estimate using the same assumptions and categories as those of the previous drainback systems.

With both the performance and cost data in hand, we compared the economics of both the drainback systems and the ICS systems. This assessment provides a basis for recommendations for further work in both drainback and ICS systems.

The remainder of this report documents the task work on drainback and ICS system performance and cost. Section 2.0 presents the updated cost and performance data for drainback systems. Since ICS systems have not been studied extensively, Section 3.0 is an overview of ICS systems, including a literature review, design considerations, manufacturers' survey results, and cost estimates. The standards that apply to ICS systems are discussed in Section 4.0 and a simple model that was applied to one of these standards is developed. Section 5.0 reviews an annual performance methodology and presents results for various ICS system designs. This section also compares ICS performance with drainback performance. Cost and performance data are combined in Section 6.0 using a discounted payback analysis. Conclusions and recommendations are given in Section 7.0.

SECTION 2.0

DRAINBACK SYSTEMS

Previous SERI work by Kutscher et al. (1984) on low-cost systems developed cost and performance data for several drainback system configurations. This work was based on component and system cost data that are now outdated. Since the emphasis was on cost reduction and not performance, system performance had been estimated. We updated both the costs and performance using the latest available information and design tools. Two different systems were evaluated: a commercially available system utilizing standard components and a high-performance collector, and a low-cost alternative utilizing inexpensive components and a low-cost, lower-performance collector. We chose to develop cost data based on readily available hardware and not on components that are either under development or proposed for development.

2.1 SYSTEM CONFIGURATION

A schematic of the system studied in this section is shown in Figure 2-1. Primary components include collectors [exterior dimensions of 1.22 m (4 ft) by 2.44 m (8 ft) or 3.05 m (10 ft)]; an insulated storage tank with a volume of 0.42 to 0.45 m^2 (110-120 gal); a 30.5-m (100-ft)-long copper tube heat exchanger; a differential controller with two sensors; a low-flow, high-head pump; approximately 30.5 m (100 ft) of system piping with insulation and weatherized coatings for the sections exposed to the elements; and all of the necessary valves, fittings, and brackets required to complete the system.

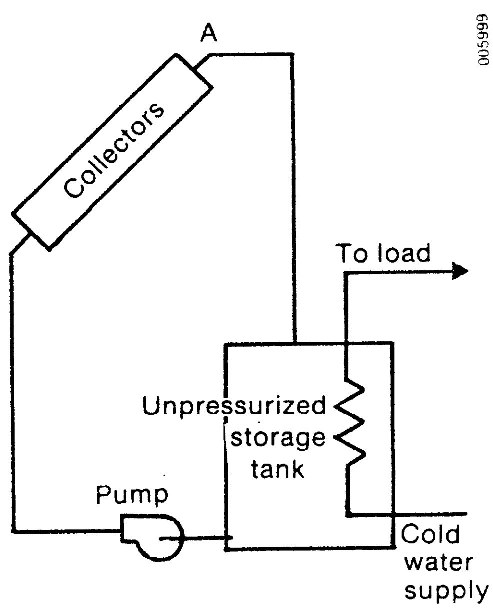

Figure 2-1. Drainback System with Load-Side Heat Exchange

The system operates as follows. Morning start-up occurs when the signals from the sensors tell the controller that useful energy can be collected. At that point, the pump turns on, and must overcome both friction in the pipe and static head. Once the fluid has reached point A, a siphon is established (if certain pipe size and fluid velocity criteria are met), and the power to the pump is reduced by means of a pump speed controller (Farrington 1983) so that the flow rate is not excessive and pump power is decreased. The pump continues to operate at this reduced level as long as useful energy can be collected. Storage tank fluid circulates directly to the collectors, and heat is delivered to the load via a load-side heat exchanger. This configuration allows an unpressurized tank to be used that can significantly reduce system costs. When the controller turns off the pump, fluid in the collector drains back into the storage tank, providing positive freeze protection should it be necessary.

2.2 SYSTEM COSTS

To represent a system that could be purchased today, we estimated the costs of one system using commercially available, high-performance collectors and conventional balance-of-system components. The other system utilized lower-cost components (polybutylene pipe, 55-gal drum storage, etc.) that also have potential installation cost benefits. This system used a commercially available low-cost collector manufactured by Sealed Air Corp. (model BGI-32), an inexpensive, low-performance unit typically used in pool heating applications. Collector performance parameters are from SRCC test results (1983). The low-cost unit did not perform as well or cost as much as the first collector, a Novan Optima II 48SC.

Costs were developed based on quotes for equipment costs, labor estimates, and data from Means (1983). Costs found in the APRR catalog were found to be very high in many cases, compared with cost quotes from local distributors. Additionally, costs for the same item quoted by different suppliers often varied considerably. In all cases, we used the most favorable costs. Labor costs were dependent on both labor hours and rates. It was difficult to estimate the amount of installation time for the various components in the systems we costed. Some data on collector installation requirements and skill levels (hence hourly rates) were reported by Means (1983); otherwise, labor figures are based on our best judgment. System costs are detailed in Tables 2-1 and 2-2 for the commercial system and for the low-cost, low-performance system. Nearly a 40% reduction in cost is expected for the low-cost system compared with the commercial system. On a cost-per-unit-area basis, the resulting costs are \$540 m^2 (\$50/ft^2) and \$270/m^2 (\$25/ft^2) for the commercial and the low-cost system, respectively. Since the balance-of-system comparison on a cost-per-unit-area basis does not give particularly meaningful results, comparisons on this basis with other solar technologies are not appropriate. Evaluations between alternatives must include performance. A cost percentage breakdown by category is given in Table 2-3. The cost of the commercial system is probably optimistic, especially when compared with actual installed system costs. Differences are due primarily to the influence of tax credits and low volume, which tend to inflate the overhead and profit categories at the dealer level. Overhead and profit percentages used in our estimates represent what would more typically be found in an established product market.

Table 2-1. Cost for Commercial Drainback System

Equipment	Cost ($)	Labor (h)	Rate ($/h)	Total Labor Cost ($)
Collectors, 1.22 m × 2.44 m (4 ft × 8 ft) 2 at $461.62 (Novan 48SC)	923.24	2.7	18.7	50.49
Brackets, 2 each	50.00	--	--	--
Storage tank, insulated, 454 L (120 gal)	300.00	2.0	18.7	37.40
Heat exchanger, 30.5 m (100 ft), 1.9-cm (3/4-in.) copper tube	67.00	1.0	18.7	18.70
Pump, Taco 009BF, 6.1-m (20-ft) head at 7.7 L/min (2 gpm)	123.45	1.0	18.7	18.70
Controller and sensors	54.14	2.0	18.7	37.40
Valves, 2 ball-type	15.00	1.5	18.7	28.05
Piping, 1.9-cm (3/4-in.) copper, 30.5 m (100 ft)	67.00	7.0	18.7	130.90
Pipe insulation, 1.9-cm (3/4-in.) wall	65.00	7.0	18.7	130.90
Fittings	20.00	4.8	18.7	89.76
	1,684.83			542.30
				1,684.83
Total labor and materials				2,227.13
Labor paid by general contractors (21%)				113.88
Sales tax (6%)				101.09
				2,442.10
General contractor overhead (15%)				366.31
				2,808.41
General contractor profit (15%)				421.26
Total system costs				3,229.68

Table 2-2. Cost for Low-Cost, Low-Performance Drainback System

Equipment	Cost ($)	Labor (h)	Rate ($/h)	Total Labor Cost ($)
Collectors, 1.22 m × 3.05 m (4 ft × 10 ft), 2 at $202.00 (Sealed Air BGI-32)	404.00	2.7	18.7	50.49
Brackets, 2 each	50.00	--	--	--
Storage tank, insulated, 208-L (55-gal) drums	58.00	3.0	18.7	56.10
Insulation for tanks, 0.17-m (6-1/2-in.) F. G., rigid foam bottoms	15.00	1.0	18.7	18.70
Heat exchanger, 30.5 m (100 ft), 1.9-cm (3/4-in.) copper tube	67.00	1.0	18.7	18.70
Pump, Taco 009BF, 6.1-m (20-ft) head at 7.7 L/min (2 gpm)	123.45	1.0	18.7	18.70
Controller and sensors	54.14	2.0	18.7	37.40
Valves, 2 ball-type	15.00	0.75	18.7	14.03
Piping, 1.9-cm (3/4-in.) polybutylene, 30.5 m (100 ft)	31.00	5.0	18.7	93.50
Pipe insulation, 1.9-cm (3/4-in.) wall	65.00	7.0	18.7	130.90
Fittings	10.00	2.0	18.7	37.40
	892.50			475.92
				892.59
Total labor and materials				1,368.51
Labor paid by general contractors (21%)				99.94
Sales tax (6%)				53.55
				1,522.01
General contractor overhead (15%)				228.30
				1,750.31
General contractor profit (15%)				262.55
Total system costs				2,012.85

Table 2-3. Cost Percentage by Category for the Two Drainback Systems (%)

System	Category				
	Collectors	Equipment	Labor	Tax	Overhead and Profit
Commercial	29	24	20	3	24
Low-cost	20	24	29	3	24

Using lower-cost collectors causes labor rather than collectors to be the largest cost category. However, the absolute value of labor costs is somewhat lower for the low-cost systems, owing primarily to the ease with which the polybutylene pipe is installed. Additional cost reductions in the collector and labor categories are possible, but somewhat limited. Equipment costs could be reduced with high-volume purchasing, or by simplifying the system so that fewer components are needed. Further significant reductions of equipment cost may be difficult to achieve without packaging the low-cost, balance-of-system components in some manner.

2.3 SYSTEM PERFORMANCE

Performance of each system was predicted using F-CHART version 4.1 (Mitchell et al. 1980). Because F-CHART cannot model a load-side heat exchanger system, the performance values were calculated for a system with collector-side heat exchange. This modification results in comparable performance predictions as long as our system has a heat exchanger large enough to permit it to match the heat transfer of the collector-side system in the F-CHART model. The hot water load is based on a 300-L/day (75-gal/day) use, a set temperature of 50°C (122°F), and a water mains temperature of 11°C (52°F). Collector areas are based on the typical size and number of collectors for residential DHW systems sold today. System parameters for both cases are shown in Tables 2-4 and 2-5. Performance results are given in Section 6.0 in the economic comparison with ICS systems.

Table 2-4. F-CHART Parameters for the Commercial Drainback System

Collector Parameters		
C1	Collector area	5.95 m^2 (64.0 ft^2)
C2	FR-UL product	4.50 W/m^2 °C (0.79 Btu/h ft^2 °F)
C3	FR-τα (normal incidence)	0.77
C4	Incidence angle modifier constant	0.23
C5	Collector flow rate × specific heat/area	70.00 W/m^2 °C (12.3 Btu/h ft^2 °F)
C6	Collector slope	Lat
C7	Collector azimuth	0.00°
C8	Ground reflectance	0.20
Collector-Store Transfer Parameters		
T1	EPS-CMIN of collector-store HX/collector area	70.00 W/m^2 °C (12.3 Btu/h ft^2 °F)
T2	UA of collector inlet pipe or duct	00.0 W/°C
T3	UA of collector outlet pipe or duct	0.00 W/°C
Storage Unit Parameters		
S1	Tank capacity/collector area	350.00 kJ/m^2 °C (17.1 Btu/ft^2 °F)
S2	Storage unit height/diameter ratio	2.00
S3	Heat loss coefficient	0.50 W/m^2 °C (0.088 Btu/h ft^2 °F)
S4	Environment temperature (-1000 for TENV = TAMB)	20.0°C (68°F)
S5	Hot water auxiliary tank UA	0.00 W/°C
S6	Hot water auxiliary tank environment temperature	20.00°C (68°F)
Load Parameters		
L3	Hot water use	300.00 L/day (79.3 gal/day)
L4	Hot water set temperature	50.00°C (122°F)
L5	Water mains temperature	11.00°C (51.8°F)
Auxiliary Parameters		
A3	Hot water auxiliary fuel (1 = Gas, 2 = Elec, 3 = Oil)	2
A4	Auxiliary water heater efficiency	1.00

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Table 2-5. F-CHART Parameters for the Low-Cost, Low-Performance Drainback System

Collector Parameters		
C1	Collector area	7.43 m^2 (80.0 ft^2)
C2	FR-UL product	7.90 $W/m^2{}^oC$ (1.39 Btu/h ft^2 ^oF)
C3	FR-$\tau\alpha$ (normal incidence)	0.67
C4	Incidence angle modifier constant	0.19
C5	Collector flow rate × specific heat/area	70.00 $W/m^2{}^oC$ (12.3 Btu/h ft^2 ^oF)
C6	Collector slope	Lat
C7	Collector azimuth	0.00^o
C8	Ground reflectance	0.20
Collector-Store Transfer Parameters		
T1	EPS-CMIN of collector-store HX/collector area	35.00 W/m^2 ^oC (6.17 Btu/h ft^2 ^oF)
T2	UA of collector inlet pipe or duct	0.00 $W/^oC$
T3	UA of collector outlet pipe or duct	0.00 $W/^oC$
Storage Unit Parameters		
S1	Tank capacity/collector area	350.00 kJ/m^2 ^oC (17.1 Btu/ft^2 ^oF)
S2	Storage unit height/diameter ratio	2.00
S3	Heat loss coefficient	0.50 W/m^2 ^oC (0.088 Btu/h ft^2 ^oF)
S4	Environment temperature (-1000 for TENV = TAMB)	20.0^{o}C (68^{o}F)
S5	Hot water auxiliary tank UA	0.00 $W/^oC$
S6	Hot water auxiliary tank environment temperature	20.00^{o}C (68^{o}F)
Load Parameters		
L3	Hot water use	300.00 L/day (79.3 gal/day)
L4	Hot water set temperature	50.00^{o}C (122^{o}F)
L5	Water mains temperature	11.00^{o}C (51.8^{o}F)
Auxiliary Parameters		
A3	Hot water auxiliary fuel (1 = Gas, 2 = Elec, 3 = Oil)	2
A4	Auxiliary water heater efficiency	1.00

SECTION 3.0

ICS SYSTEM OVERVIEW

3.1 LITERATURE REVIEW

Integral collector/storage (ICS) systems have been in use for many years, in the United States as well as around the world, but surprisingly little analysis existed until the 1970s. Although the concept is quite simple (most systems consist of a tank or series of tanks inside of a glazed, insulated box, plumbed in-line with the cold water supply), a thermal performance analysis of ICS systems is complicated because it is difficult to separate the contributions of the glazing, the absorber surface, hydrodynamics of the fluid in the tank, and the insulated box, particularly in view of the vast number and wide variety of system configurations that are currently available. As part of our assessment of ICS systems, we conducted a comprehensive literature survey of analyses pertaining specifically to ICS systems as well as more general studies of heat transfer for configurations found in ICS systems.

The first patents for ICS water heaters were issued in the late 1800s, and many systems based on the early designs were built in southern California and Florida. Perhaps the earliest publication describing ICS systems was an article that appeared in a Berkeley Agricultural Research Bulletin by F. A. Brooks (1936). This bulletin documented what had been understood for some time; that is, that water heating could be achieved very simply by placing a container of water in the sunlight. Passive water heaters gained popularity during the early twentieth century, particularly in hot, sunny climates.

More recently, beginning in the mid-1970s, a renewed interest in ICS water heaters arose. One design that is often cited is the Zomeworks system designed by Steve Baer (1978). The Zomeworks Breadbox system consists of a horizontal tank within an insulated, rectangular box that has the top and south faces double-glazed. The insulated box lid and south-facing side (door) of the box are manually opened each morning. Reflective surfaces on the inside of the door and lid reflect additional radiation onto the black tank. At night, the lid and door are closed to minimize night heat losses.

Another class of ICS systems, aimed at reducing night sky radiation losses as well as convective losses, is the inverted configuration, in which the glazing faces downward and incident radiation is reflected into the tank. Stickney (1984) described several inverted ICS systems, including three snail-type designs. Because of their large and somewhat cumbersome form, inverted systems may have limited application.

Burton and Zweig (1981) studied side-by-side performance of two identical inclined-tank ICS systems with various glazing treatments, tank treatments, and interior collector surfaces. They concluded that a selective surface on the tank provided a greater efficiency improvement than any of the other options examined, but the duration of their experiments was rather brief.

Bishop (1983) described a batch-type water heater that was specifically developed for freezing climates. It incorporates high levels of insulation RSI* 7 (R-40), a multiple-glazing system of low-iron glass and high transmission films, and two 170-L (45-gal) tanks with selective surfaces within an involute-curved reflector. Polybutylene pipe is used for all exterior piping and is covered with RSI 4.5 (R-25) insulation. Performance monitoring of this prototype was very limited, and a rigorous analysis of system performance was not undertaken. However, it appears that many of the design features of this system are appropriate choices for a freezing climate.

Reichmuth and Robison (1983) developed a simulation method for ICS systems using a thermal network approach and described a simplified test procedure to experimentally determine the model parameters. Robison (1984) described a simplified procedure to take standard system test results and adjust them to any other location.

Cummings (1983) described a simulation model of an ICS system that is similar in design to a Gulf Thermal Progressive Tube, in which there are several small tanks (tubes) plumbed in series within a glazed box. The tanks are assumed to completely fill the aperture. His model allows hour-by-hour simulation of thermal performance and takes into account solar gain, heat losses to the air and night sky, and the internal heat transfer for the system under consideration. The model is flexible enough to allow a variety of parametric studies.

Cummings looked at the number and clarity of glazings, number and volume of tanks, box insulation, night insulation, absorber emissivity, and load schedules. The model is appropriate only for the configuration modeled, and does not specifically compute hydrodynamic interactions of the fluid within the tanks. From his analysis, Cummings made several conclusions. He found that the system he modeled was only slightly less efficient (from 3% to 15% less) than an active SDHW system, based on comparison with F-CHART runs in the same locations for solar savings fractions from 0.27 to 0.64. A system with a selective surface was always more efficient and more cost-effective than a system with a nonselective surface, and single glazing was more cost-effective except for high solar savings fractions in cold climates. Freezing appeared to be much less of a problem than had been anticipated for batch heaters. Single glazing with a selective surface was found to prevent a system from freezing in Washington, D.C., or milder climates, and a double-glazed system with selective surface was sufficient to prevent freezing in all climates modeled except Bismarck, N. Dak. Adding R-9 night insulation substantially improved performance for all locations and eliminated freezing of the single-glazed system for all climates. A draw schedule weighted toward the morning caused a 10%-15% performance penalty, while an evening-weighted draw improved overall performance by 5%-10%. Economic analyses by Cummings show relatively high rates of return on investment (13%-25%) but are based on 40% tax credits.

The work of Lindsay and Thomas (1983 and 1984) resulted in a detailed model of an ICS configured with a single, horizontal tank in a reflective enclosure. The primary purpose of their work was to examine alternatives to then-current

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*R-value expressed in standard SI units of m^2 $^{o}C/W$.

system test methods for ICS systems. Specifically, they investigated the possibility of using an in-line heater to substitute for a solar simulator that is required by the current industry standard. Their single-node model was based on the Cornell 360 design. The model was developed to compare experimental results with predictions for both stratified and mixed-tank experiments. They found experimentally that forced circulation made little difference compared with stratification in daily energy collection efficiency. They limited their experiments to only no-draw and noon-draw profiles. However, they obtained very good agreement using the single-node model for all experimental data. They concluded that using a mixed mean temperature in the model was adequate to characterize the ICS system they tested.

A TRNSYS model of an ICS system with a single horizontal tank inside a reflective box, similar to the Cornell 360 system, was developed by Zollner (1984). He used the TRNSYS model to develop a correlation method that predicts (within the range of parameters studied) annual performance of ICS systems. The annual prediction procedure requires as inputs a heat loss coefficient, an effective optical efficiency, the system size, monthly weather data, and monthly average hot water draw. The system parameters may be the result of a test, or they may be presumed or desired properties of the ICS system being modeled.

The most common configuration for an ICS system is a horizontally oriented tank or a series of tanks. Therefore, we reviewed the literature in which the heat transfer of fluid in a heated, horizontal tank has been examined. Young and Baughn (1981) observed vertical temperature gradients in horizontal storage tanks and proposed a one-dimensional model for stratification in the tank that allows some degree of mixing at the inlet and outlet boundaries. Agreement with experimental results was reasonable for temperatures near the tank top, but bottom temperatures deviated from predictions. They observed significant mixing within the tank when fluid was withdrawn unless a diffuser manifold was placed on the make-up water inlet.

Liburdy (1982) examined natural convection of fluids within a horizontal cylinder having uniform wall heat flux. He found that a modified Rayleigh number could be used to correlate heat transfer data within the cylinder for the range of parameters used in his investigation. The limitation of this work lies in the assumption of uniform wall heat flux, which is not the case for an ICS system. Kee (1974) developed numerical techniques to predict two-dimensional transient natural convection heat transfer within a horizontal cylinder. The methods solve the full momentum (Navier-Stokes) and thermal energy equations and are general enough to accommodate completely arbitrary boundary conditions (within the assumption of two-dimensional flow). Thus, the asymmetric case where only a portion of the tank circumference is heated (as in an ICS system tank) may be solved with these methods. The most general analysis would result from using a full three-dimensional Navier-Stokes solution such as is available with the Argonne-developed code COMMIX (Domanus et al. 1983). We have obtained documentation and a user's manual for COMMIX and are evaluating the potential benefits that may result from this level of analysis.

3.2 DESIGN CONSIDERATIONS

ICS systems are typically configured as either a single tank with circumferential glazing, a single tank in a glazed box with a reflector, or multiple tanks in a glazed box butted together as shown in Figures 3-1, 3-2, and 3-3. Figure 3-4 shows a system with a half reflector placed below the tank in such a fashion that convection losses are minimized. If the solar radiation can be intercepted by another surface and then transferred to the tank by means of conduction or convection, the tank can be heavily insulated as shown in Figure 3-5. In a unitary thermosiphon heater the flat portion could be a conventional flat-plate collector containing the potable fluid or antifreeze (necessitating a heat exchanger). Alternatively, a bank of heat pipes could be used.

All of these systems have several things in common. The collection and storage devices, though not always one and the same, at least come together in a single package. No controls, pumps, or parasitic energy are required. Other than the piping to the conventional system, no other hardware is required. In each case, potable water is stored outside of the living space where thermal losses and freezing danger occur.

We will focus our attention on the two most common ICS designs (shown in Figures 3-2 and 3-3): a single tank with a reflector and a multiple-tank unit.

3.2.1 Single Tank with Reflector

A simple involute reflector in a single-tank design will distribute solar radiation from 180^{o} full acceptance angle onto the entire tank circumference in an ideal case (i.e., tank is end supported). The tank can be mounted vertically or horizontally, though the former orientation would probably result in better stratification. Thus, if the tank has diameter D, the ideal aperture width will be πD. Continuation of a compound parabolic-shaped reflector above the level of the tank can supply perhaps 10%-20% more energy (1.1-1.2 concentration ratio) but the lowered acceptance angle would require horizontal mounting, result in higher reflector cost, and require a deeper enclosure with resultant cost and aesthetics problems. For purposes of this simple analysis, we will just assume an ideal involute reflector.

As with any solar hot water system, there will be an optimum ratio of storage volume to collector area. For now we will just use "S" to represent this number.

Taking reflector width as W, tank diameter as D, and tank length as L,

$$\frac{\text{tank volume}}{\text{aperture area}} = \frac{\frac{\pi D^2}{4} L}{WL} = S \qquad (3\text{-}1)$$

$$W = \frac{\pi}{4}\frac{D^2}{S} . \qquad (3\text{-}2)$$

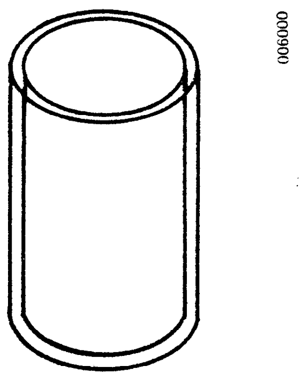

Figure 3-1. Simple Glazed Tank

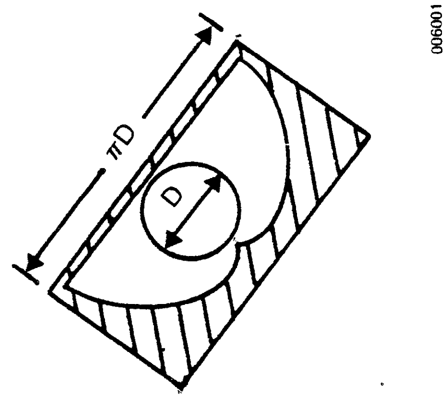

Figure 3-2. Single Tank with Ideal Involute Reflector

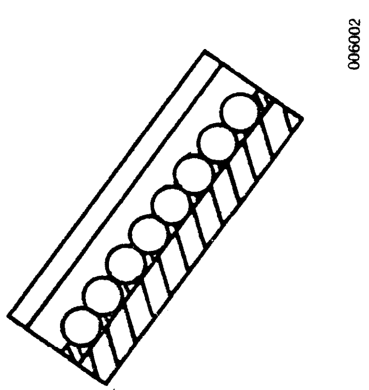

Figure 3-3. Multiple Tanks Butted Together

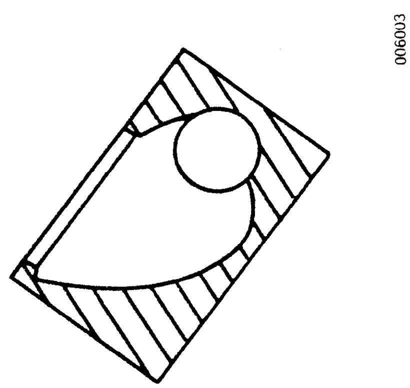

Figure 3-4. Single Tank with Half Reflector

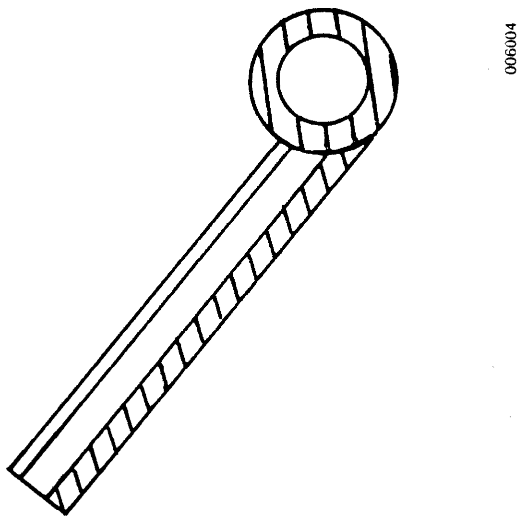

Figure 3-5. Unitary Thermosiphon System

For the involute reflector, $W = \pi D$:

$$\pi D = \frac{\pi}{4}\frac{D^2}{S} \qquad (3\text{-}3)$$

$$D = 4S \ .$$

3.2.2 Multiple Tank

If we consider a multiple-tank design with n tanks each of diameter D butted together, the aperture width W is just nD.

$$\frac{\text{tank volume}}{\text{aperture area}} = \frac{\frac{n\pi D^2}{4} L}{nDL} = S \qquad (3\text{-}4)$$

$$(\pi/4)D = S$$

$$D = 1.27\ S \ .$$

Here there is no limitation on the width of the device since any number of tanks yields the same value of S. Thus, a 2.4 m × 1.2 m (8 ft × 4 ft) device could be built without deviating from the optimum value of S. It is interesting to note that as tank diameter for a butted configuration is varied, the exposed area for heat loss remains constant at $8\pi WL/2$, or 1.57 WL (compared with WL for a single tank with reflector), assuming that only the upper hemispheres are exposed. (If the aperture width is W, each tank would have a diameter of W/n for a total exposed surface area of $1/2 \times n \times \pi \times WL/n = \pi WL/2$.)

3.2.3 ICS Heat Loss

One disadvantage of ICS systems compared with pumped systems is that the water is stored outside the building envelope and can lose more heat overnight. If we assume a simple exponential decay of the bulk fluid temperature (with no draw and constant amount temperature), then the loss overnight will be a function of the thermal capacitance, the initial temperature difference, and the thermal loss coefficient. It will be shown later that for a well-designed ICS system with typical values of G, the overnight losses (and overall performance) are not a strong function of the capacitance. It is clear, however, that a reduction in the loss coefficient will result in lower overnight losses and better overall performance for an ICS system. If the tank temperature at the end of the day is low due to a draw, the overnight loss will be lower. Thus, an ICS system can be expected to perform better if the usable heat is extracted by late afternoon or early evening.

In analyzing an ICS system it is not clear what heat transfer coefficient should be used inside the tank and whether it is important to consider. Let us first compare the thermal resistance between the tank wall and ambient to that between the wall and tank fluid. A well-designed ICS unit might have a loss coefficient U_L of 2 W/m^{2}K (0.35 Btu/h ft^2 °F).

Coefficients for heat transfer from a warm cylinder wall to a cool interior fluid are not readily available in the literature. Since the tank is relatively large, however, we will approximate this with a vertical warm wall.

A typical heat transfer correlation for turbulent natural convection on a heated, vertical wall (Chapman 1974) is

$$h_f = 0.129 \left(\frac{g\beta\Delta T\rho c_p k^2}{\nu}\right)^{1/3} . \tag{3-5}$$

Note that the characteristic length does not appear in the turbulent range due to the 1/3 power dependence of the Nusselt number.

Taking the wall temperature as 60°C (140°F) and the average fluid temperature as 37.8°C (100°F) [the average of a 15.6°C (60°F) supply temperature and the wall temperature] and using properties for water at 49°C (120°F),

$$h_f = 1007 \text{ W/m}^2\text{K} . \tag{3-6}$$

Obviously the thermal resistance between the tank wall and the environment greatly exceeds that between the wall and the fluid. The overall heat loss will then be controlled by the resistance between the tank and the environment.

If we assume no significant change in physical properties with changes in temperature, then we can separate the effect of ΔT in the heat transfer coefficient:

$$h_f = 572 \, \Delta T^{1/3}, \, \Delta T \text{ in } ^\circ\text{C} . \tag{3-7}$$

Now compare the energy flux on the tank wall to the inside film coefficient. If we assume a peak solar flux of 950 W/m^2 (300 Btu/h ft^2) and an efficiency of 50%, the peak, net flux into the fluid is 475 W/m^2 (150 Btu/h ft^2). On the other hand, our inside flux is 572 $\Delta T^{1/3} \times \Delta T$ or 572 $\Delta T^{4/3}$. Setting these two equal we obtain a temperature difference of only 0.9°C (1.6°F). Thus, even if we have overestimated the film coefficient by, say, a factor of 2, it would mean that the absorber would run only 0.6°C (1.8°F) hotter [ΔT = 1.5°C (2.6°F)] at peak conditions and even less than that at average conditions with little effect on efficiency. Regardless of the tank temperature, the bulk fluid energy gain will be limited by the available solar radiation, not internal convection. We have assumed turbulent flow inside the tank in this analysis, but even if this is not the case, the limiting thermal resistance will be between the tank wall and the environment.

ICS systems are protected from freezing to a certain extent by the large mass of water contained in these units. In very cold climates, immersed heaters or electrically operated shutters can be used to protect the tank. One area of concern expressed by manufacturers, however, is the problem of the connecting pipes freezing. A possible solution we have identified is to include a thermosiphon bypass loop in the piping that will allow tank fluid to move into the connecting pipes.

Figure 3-6 shows a conventional ICS plumbing layout. Figure 3-7 shows the inlet pipe at the top, the outlet pipe at the bottom, and a bypass with a check valve located near the storage tank (i.e., at room temperature). Whenever a load is drawn, these two systems behave the same way. When no load is being drawn, no flow occurs in the conventional system. The thermosiphon bypass system, however, will experience clockwise thermosiphon flow through the bypass loop whenever there is no load flow and the ICS tank is below room temperature. Thus, at night the exposed supply and return pipes will be kept near the ICS tank temperature. As long as the pipes are very well insulated this will not result in significant heat loss. The challenge in using this technique is to do it in a fashion that does not disrupt tank stratification during the day. Using long dip tubes may work, although small holes in these tubes may be needed to accommodate thermosiphon flow. It is assumed in this scheme that if the ICS tank is above room temperature, the short lengths of exposed connecting pipe will be sufficiently warmed by conduction. A disadvantage of this idea is that the tank inlet and outlet pipes must connect at opposite ends of the tank.

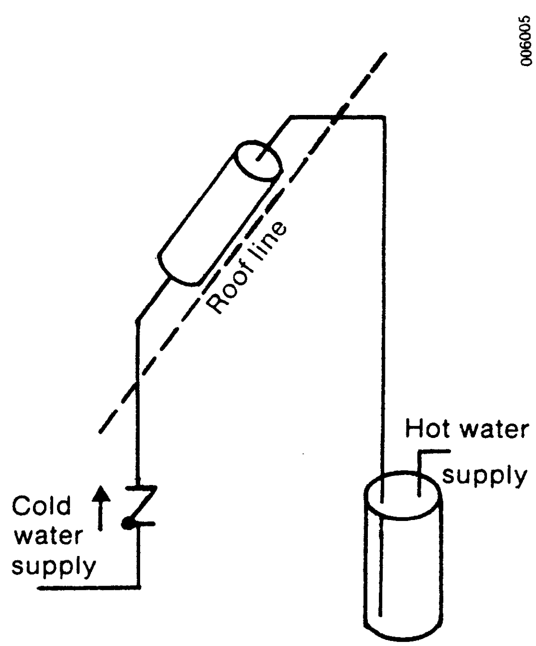

Figure 3-6. Typical ICS Plumbing Layout

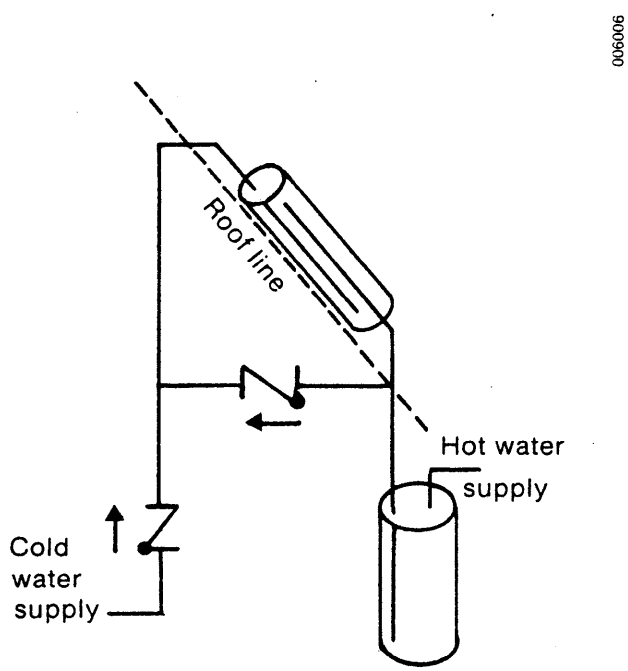

Figure 3-7. Plumbing Arrangement to Help Protect Outdoor Pipes from Freezing

3.3 MANUFACTURERS' SURVEY

In order to gather as many data as possible concerning the current market for ICS systems we conducted a survey of manufacturers. In our survey, we contacted 19 manufacturers or distributors, either by telephone or mail. Of these, ten responded in some detail. We asked questions covering marketing, design, and cost issues. A copy of the survey form is included as Appendix B in this report. To maintain the confidentiality requested by many manufacturers, no listing of manufacturers' names or other identifying data is given in this report. Only the range of costs in the various categories is discussed.

The cost data obtained were the most quantitative of the responses in the survey. We asked for cost data in three categories, including costs for production, distribution, and installed cost to the consumer. Consumer cost was for the ICS unit alone; i.e., not installed. Each of these cost categories was broken into absolute cost, cost per unit area, and cost per unit dry weight. The per-unit-area and per-unit-weight costs were calculated in an attempt to find a measure that might allow for a common basis for comparison or normalization of the cost data.

Few of the manufacturers gave their manufacturing costs; however, most were willing to give dealer costs. Costs to the consumer were obtained if the unit could be sold separately (from installation) to the consumer. Installed costs, if given, were usually estimated, reflecting the lack of control most manufacturers have on this category. Relatively few of the manufacturers were also installers.

The absolute manufacturing costs had a wide range, from a minimum of \$200 to a maximum of \$700. Since the units are of varying sizes, a comparison on a per-unit-area or weight basis is probably more appropriate. Costs per unit area vary from \$150/m^2 to \$276/m^2 (\$13.9-\$25.6/ft^2). This is a much narrower range than the absolute costs. On a per-unit-weight basis, the range is even narrower, from \$4.7/kg to \$5.6/kg. This indicates a fairly uniform cost parameter, which is probably not related to performance.

Dealer costs were the most frequently obtained in the survey. These costs were sometimes a function of the number of units delivered. Absolute costs ranged from \$350 to \$1000. Per-unit-area costs varied from \$286/m^2 to \$438/m^2 (\$26.6-\$40.7/ft^2). On this basis, the costs are somewhat normalized, but still represent a wide range. On a per-unit-weight basis, the range is \$6.4-\$10.9/kg (\$2.9-\$5.0/lb). This is still a wide range, but there are a number of manufacturers whose cost per unit weight is around \$7/kg (\$3.2/lb). The sample is not large enough to draw any conclusions based on averages, however.

Very few responses were received for the consumer cost of an ICS unit itself. The unit costs ranged from \$1000 to \$1700, with per-unit-area costs of \$476-\$773/m^2 (\$44.2-\$71.8/ft^2). The cost per unit weight ranged from \$14.1/kg to \$15.9/kg (\$6.4-\$7.2/lb).

The increase in cost from the manufacturer to the dealer ranged from about 30% to over 130%. This represents a wide range in marketing, overhead, and profit margins for these manufacturers. From dealer to consumer, for the ICS unit itself, the markup ranged from a low of near 30% to a high of over 115%. Markup obviously varies tremendously among manufacturers.

One overall conclusion we can draw from these survey data is that absolute costs vary widely. The range of costs narrows somewhat when compared on a per-unit-area basis. On a per-unit-weight basis, the cost between manufacturers is almost a constant. This may imply that although manufacturers certainly use various techniques and processes, the costs of manufacturing an ICS system of a given weight are nearly the same. Thus, if costs are to be reduced, weight may have to be reduced.

We have used these data to update our installed cost estimate in the same way that we updated our previous low-cost drainback system cost estimates. However, we could not assess the performance impacts of cost with these data. It may be possible to correlate the Solar Rating and Certification Corporation (SRCC) 200-82 Q_{NET} values for those ICS units tested on a per-unit-area or weight basis. Unfortunately, the number of manufacturers who both responded to the survey and had their system tested was insufficient.

In addition to providing valuable cost data, the manufacturers' survey gave us a great deal of insight into industry problems and needs. The great majority of the manufacturers contacted did not use computer models, detailed analyses, or design tools in arriving at their designs. As might be expected, designs are often based on material availability and durability, not just on performance considerations. For example, for one manufacturer who builds his own tanks to save costs, the tank size is based on using one sheet of 8-ft × 3-ft stainless steel with one joint. Many manufacturers prefer stainless steel tanks because of their longer life.

Freezing is a concern for the manufacturers in cold climates, and many manufacturers voiced a special concern for the freezing of connecting pipes. Several manufacturers use heat tape or "drip" valves (recommended by one manufacturer on both inlet and outlet pipes) that allow city water to flush slowly through the system and onto the roof to prevent freezing. However, another manufacturer felt that drip valves waste a great deal of water. Most are unwilling to provide freeze protection warranties. This is especially true of the companies that recommend winter draining since they feel they cannot control their customers' actions.

Many of the manufacturers believed that ICS systems perform better than many people think they do. They cited the following performance advantages for ICS systems compared with pumped designs: totally wetted absorber surface, no additional piping or storage losses during the day, and collection on marginal days when a pumped system is not operating. In addition, they felt that overnight losses are most significant if the tank energy is extracted during the day. One manufacturer expressed a strong interest in seeing detailed computer simulations that would accurately model ICS performance.

Without exception, manufacturers were interested to learn that SERI is studying ICS systems. Several expressed this in follow-up letters after the telephone survey. They appear very willing to critique our work and make recommendations and should prove a valuable resource for future efforts.

3.4 INSTALLED COST ESTIMATE

We costed ICS systems using the same assumptions and methodology as those for the drainback systems (Section 2.2). Using dealer costs for an ICS system based on the lower end of the cost-per-unit-area data obtained in our survey, installed system costs have been generated for a single-unit and a two-unit system. This information is shown in Tables 3-1 and 3-2.

The most notable item in the tables, in comparison with the earlier cost breakdowns for drainback systems, is the cost of the ICS unit itself. It appears that ICS units currently cost considerably more than flat-plate collectors. Although the ICS unit cost is high, there are considerably fewer components in the system. The overall effect is that a two-unit ICS system, using these estimates, costs slightly less than the low-cost drainback systems studied previously, and considerably less than a commercial drainback system.

One of the attractions of the ICS systems is their relative simplicity (e.g., no pump, no controller or sensors, no electric power requirements, fewer valves, etc.) compared with pumped systems. This advantage should also apply to life-cycle costs of operating and maintaining the system. Recently, Short (1985) has developed a methodology to estimate the present value of life-cycle repairs and replacements for SDHW heating systems. We have used this methodology to estimate life-cycle costs of repairs and replacements for both drainback and ICS systems. For each component or subcomponent in the system, several data are required. The mean lifetime and assumed failure probability distribution are needed, along with discount rate and system lifetime, to determine a life-cycle cost multiplier. Repair and replacement costs are used to determine the life-cycle cost for each component or subcomponent. The total system life-cycle cost is obtained by summing over all components. The results of this methodology using a 20-yr system life and a real discount rate of 4% (excludes inflation) are shown in Table 3-3 for both the drainback and ICS systems. The life-cycle repair and replacement cost is obviously significant in SDHW systems. For both the drainback and ICS systems, these costs are over 50% of the installed cost (at this discount rate). ICS systems have about a 20% advantage over drainback systems in life-cycle repair and replacement costs, and about an 11% advantage in total cost. These results apply only to the configurations and cost data used in this analysis and should not be generalized to other conditions.

Table 3-1. Cost for a Single-Unit ICS System

Equipment	Cost ($)	Labor (h)	Rate ($/h)	Total Labor Cost ($)
Collectors, 2 m^2 (21.5 ft^2), 1 unit @ $275/$m^2$	550.00	2.7	18.7	50.49
Brackets, 1 each	25.00	--	--	--
Valves, 1	10.00	0.5	18.7	9.35
Piping, 1.9-cm (3/4-in.) polybutylene, 15.2 m (50 ft)	15.00	2.5	18.7	46.75
Pipe insulation, 1.9-cm (3/4-in.) wall	32.50	2.0	18.7	37.40
Fittings	5.00	1.0	18.7	18.70
	637.50			162.69
				637.50
Total labor and materials				800.19
Labor paid by general contractors (21%)				34.16
Sales tax (6%)				38.25
				872.60
General contractor overhead (15%)				130.89
				1,003.49
General contractor profit (15%)				150.52
Total system costs				1,154.01

Table 3-2. Cost for a Two-Unit ICS System

Equipment	Cost ($)	Labor (h)	Rate ($/h)	Total Labor Cost ($)
Collectors, 4 m^2 (43.0 ft^2), 2 units @ $275/$m^2$	1,100.00	5.4	18.7	100.98
Brackets, 2 each	50.00	--	--	--
Valves, 1	10.00	0.5	18.7	9.35
Piping, 1.9-cm (3/4-in.) polybutylene, 15.2 m (50 ft)	15.00	2.5	18.7	46.75
Pipe insulation, 1.9-cm (3/4-in.) wall	32.50	2.0	18.7	37.40
Fittings	5.00	1.0	18.7	18.70
	1,162.50			213.18 1162.50
Total labor and materials				1,375.68
Labor paid by general contractors (21%)				44.77
Sales tax (6%)				69.75
				1,490.20
General contractor overhead (15%)				223.53
				1,713.73
General contractor profit (15%)				257.06
Total system costs				1,970.79

Table 3-3. Life-Cycle Cost of Drainback and ICS Systems ($)
(discount rate = 0.04, system lifetime = 20)

System	Installed Cost	Life-Cycle Cost	Total Cost
Commercial drainback	3230	1297	4527
Low-cost drainback	2013	1275	3288
ICS system (2 units)	1971	1021	2992

SECTION 4.0

INDUSTRY TEST STANDARDS FOR ICS SYSTEMS

4.1 SYSTEM TEST PROCEDURES

Many states require that a certification test be performed on solar domestic hot water systems before state tax credits can be claimed. Two industry organizations have developed certification programs to meet these requirements. The most widely used industry standard for certifying and testing water heating systems is the SRCC Standard 200-82 (SRCC 1983). The other program was developed by the Air Conditioning and Refrigeration Institute (ARI). The SRCC standard, "Test Methods and Minimum Standards for Certifying Solar Water Heating Systems," is based on ASHRAE 95-81 (1981), as is the ARI standard. ASHRAE 95-81 specifies the procedures for testing the solar water heating systems, but does not specify the conditions under which the tests are performed. These are outlined by the certification organizations.

The Oregon Department of Energy also has developed test procedures, described by Reichmuth and Robison (1982), for hot water systems in general and one for ICS systems in particular. Their method is primarily an outdoor test as opposed to the SRCC test, which requires an indoor solar simulator. Additionally, the ODOE test does not specify any draws and therefore does not result in a performance measure that depends on energy delivery. This test is useful, however, in determining the performance parameters of an ICS system that may be used in longer-term modeling. Zollner (1984) has described the use of this test method for determining performance parameters.

In the SRCC test method, solar water heating systems are designated by system type and system classification. The three main generic categories of system types are as follows:

- Forced Circulation: This type of solar system uses mechanical means to move the working fluid through the solar collector to the hot storage device.
- Integral Collector Storage: This type of solar system has all or most of its water storage located with the collector. The system operates as a passive solar device without mechanical equipment.
- Thermosiphon: This type of solar system has the storage tank located above the collector. Movement of fluid in this system is through natural convection, without mechanical equipment.

Each of the above system types may be tested in any of the following three test system classifications:

- Solar only: This system is tested as a device that will provide hot water without a conventional backup system.
- Solar preheat: This system is tested as a solar preheater that heats the water before it goes to a conventional water heater.
- Solar plus supplemental: This system is tested with its own conventional backup system or auxiliary heating element included.

The thermal performance rating of the system consists of a number of categories. Solar energy delivered Q_{NET} shows the daily net energy delivered by the solar device and is a measure of the solar energy delivered by a system under test conditions. Reserve energy capacity Q_{RES} is the reserve capacity of the system; i.e., the energy left after a full day's water use is drawn off in the test. The heat loss coefficient L is the rate of heat loss of the system. L is measured only for systems that have outside storage tanks. The auxiliary energy capacity Q_{CAP} is the measure of the energy storage capacity of the auxiliary tank. Q_{CAP} is calculated only for systems that provide their own backup. The auxiliary energy consumption Q_{AUX} is a measure of the backup energy used by the system to deliver the required amount of hot water in the test. Parasitic energy consumption Q_{PAR} is a measure of energy used to supply power to pumps, controllers, shutters, or trackers needed to operate the system. The standard test load Q_{DL} is the desired load on the solar heating system. The standard load in the SRCC program is 42,300 kJ/day (40,119 Btu/day), taken in three equal draws at 8:00 AM, noon, and 5:00 PM. This is equivalent to what an average family of four might use each day.

4.2 SRCC SIMULATION

Many of the commercially available ICS units have been tested under SRCC 200-82 (SRCC 1983). Most ICS systems have been tested as "solar preheat" types, but they can also be tested as "solar only" types. A multinode model has been used to simulate the two different SRCC tests. The single-node model is the basis for the multinode approach described later in this section. Several assumptions simplify the solution of the differential equations: fully mixed tank, quasi-steady state over the time step, and a constant heat loss coefficient. The system can be drawn with inputs and outputs as shown in Figure 4-1.

An energy balance on the system yields

$$Mc_p \frac{dT}{dt} = Q_s + \dot{m}c_pT_{in} - \dot{m}c_pT - UA(T - T_a) \ , \qquad (4\text{-}1)$$

where

$\dot{m}c_p$ = load flow capacity (W/°C)

Mc_p = system heat capacity (J/°C)

T = tank temperature (°C)

t = time (s)

Q_s = absorbed solar energy (W)

T_{in} = fluid inlet temperature (°C)

UA = overall loss coefficient (W/°C)

T_a = ambient temperature (°C) .

If

$$\beta = \frac{Q_s + \dot{m}c_pT_{in} + UAT_a}{Mc_p} \qquad (4\text{-}2)$$

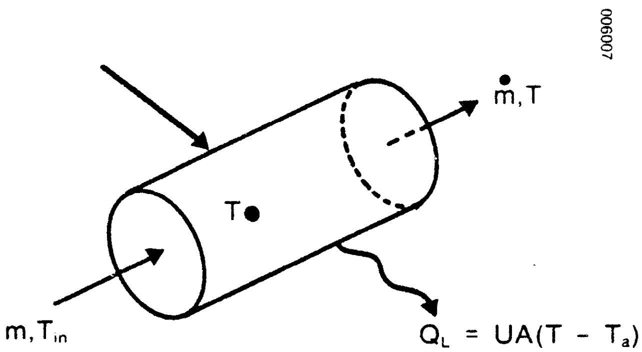

Figure 4-1. Schematic of ICS Model

and

$$\gamma = \frac{\dot{m}c_p + UA}{Mc_p} , \qquad (4\text{-}3)$$

then the energy balance becomes

$$\frac{dT}{dt} = \beta - \gamma T . \qquad (4\text{-}4)$$

With $T(0) = T_0$ the solution is

$$T = \beta/\gamma + (T_0 - \beta/\gamma)e^{-\gamma t} , \qquad (4\text{-}5)$$

and the average tank temperature over time t' is

$$\bar{T} = \frac{1}{t'} \int_0^{t'} T dt \qquad (4\text{-}6)$$

or

$$\bar{T} = \beta/\gamma - (T_0 - \beta/\gamma) \frac{e^{-\gamma t'} - 1}{\gamma t'} . \qquad (4\text{-}7)$$

The energy delivered is

$$Q_{del} = \dot{m}c_p(\bar{T} - T_{in})t' , \qquad (4\text{-}8)$$

and the energy lost is

$$Q_{loss} = UA(\bar{T} - T_a)t' . \qquad (4\text{-}9)$$

The internal energy change is

$$Q_{int} = Mc_p(T' - T_0) , \qquad (4\text{-}10)$$

where $T' = T(t')$.

If optical characteristics like a flat-plate collector are assumed for an ICS collector, then Q_s can be determined as follows:

$$Q_s = Q_{inc}\eta_o \{1 - B_0[1/\cos(\theta) - 1]\} , \qquad (4\text{-}11)$$

where

Q_{inc} = incident solar energy in aperture plane W
η_o = normal transmittance-absorptance product
B_0 = incident angle modifier coefficient
θ = incident angle .

To generalize this analysis to multiple nodes, all that is necessary is to

- divide Q_s, UA, and Mc_p by the number of nodes N
- set $T_{in}(n) = \overline{T}(n - 1)$, where n refers to the node in question
- sum Q_{loss} and Q_{int} over the number of nodes
- set $Q_{del} = \dot{m}c_p[\overline{T}(N) - T_{in}(1)]t'$.

A multiple-node model approximates stratification in the tank because of forced circulation during a draw. Natural circulation is not accounted for in this approach.

4.3 SRCC 200-82 SIMULATION RESULTS

We employed the multinode model to simulate the SRCC 200-82 test method for two primary purposes. The first was to examine the effects of changing the model parameters on the simulated test results. The second purpose was to try to match the published performance indices for certain ICS units by adjusting certain unknown model parameters.

The two basic types of ICS systems should have different performance parameters in the model. An ICS system with a single-tank, reflector configuration is likely to have low optical performance and a low heat loss coefficient compared with a multiple-tank system of the same aperture area and glazing system. The difference in heat loss coefficient is due to the smaller area for heat loss from a single-tank system. (Recall from Section 3.2 that the tank surface area in an ideal single-tank design is the same as the aperture area, whereas in a multiple-tank design the exposed upper surface area is equivalent to 1.57 times the aperture area.) However, the single-tank system uses a reflector, which results in a loss in optical performance (due to reflectivity and optical inaccuracies) compared with the multiple-tank system that does not use a reflector. To determine the effect of various parameters, we have chosen for these two system configurations baseline parameters that we feel represent fairly typical values. Table 4-1 shows the values of the model parameters used in the analysis. Note that the same value for B_0 (incident angle effects) was used for both systems. Typical values for B_0 for flat-plate collectors were taken from ASHRAE 93-77 (1977) and adjusted rather arbitrarily for use with ICS systems. The ASHRAE 93-77 incident angle modifiers are for single- and double-glazed collectors with absorber surface absorptivities of 0.9. We assumed an increase of 25% in B_0 for ICS systems because of increased enclosure depth and an additional increase of 25% for the reflector of the single-tank design. We assumed, and later results will confirm, that the incident angle effects on the optical efficiency are relatively small, and that large changes in B_0 would not significantly affect the results. This occurs because, at large incident angles, significantly less energy crosses the aperture plane (cosine effects).

4.3.1 Parameter Sensitivity

The first parameter we explored was the system capacitance. The bulk of the system capacitance is from the water in the tank. As we changed the capacitance, we held the heat loss coefficient constant.

Table 4-1. **Baseline ICS Performance Parameters for Typical System Configurations**

ICS System	Mc_p [kJ/°C (Btu/°F)]	Net Area [m^2 (ft^2)]	UA [W/°C (Btu/h °F)]	η_o	B_0	Number of Nodes	Configurations
#1	400 (211)	2.0 (21.5)	8.0 (15.2)	0.7	0.2	4	Multiple-tank
#2	400 (211)	2.0 (21.5)	3.0 (5.7)	0.5	0.2	2	Single-tank, reflector

For both the multiple-tank and single-tank ICS systems we assumed that any change in the tank surface area resulting from a change in tank volume would not affect the heat loss characteristics. We also assumed that the incident angle effects would also be unaffected. Both of these assumptions are probably reasonable given the nature of the model used in this analysis. In any case, a much more sophisticated model would be needed to determine the effects of system design on the heat loss coefficient and incident angle modifier coefficient.

In a multiple-tank ICS it is possible to vary the system capacitance while holding the aperture area constant by altering the number and diameter of the tanks and the aperture length. There are several alternatives: holding the diameter constant and changing the number and length of the tanks, holding the length constant and changing the number and diameter of the tanks, or holding the number of tanks constant and changing the diameter and length of the tanks. For a given aperture area and system capacitance, there is no unique set of values for tank number, diameter, and length. We have not evaluated the potential impacts on manufacturing for various combinations of these design values. Figure 4-2 shows the results of capacitance change for ICS #1 (multiple-tank system). An additional case of low heat loss coefficient [UA = 4 W/°C (7.6 Btu/h °F)] is shown to identify any relationship between the capacitance and heat loss effects. Note that there is a definite peak in the Q_{NET} curve at a system capacitance of around 400 kJ/°C (211 Btu/°F) for both values of loss coefficient. After that point Q_{NET} falls slightly and Q_{RES} begins to climb. It appears that in designing ICS systems the only reason to exceed the optimum capacitance value would be to allow for higher loads than are used in the SRCC 200-82 test.

In a single-tank system it is also possible to vary the system capacitance while holding the aperture area constant. In this case, however, only the tank diameter and length are variables. Since we have assumed an optimum ratio of aperture width to tank diameter, there is a unique diameter and length for a given capacitance and aperture area combination. Thus, for a fixed aperture area, a change in capacitance will cause a change in the aspect ratio (width to length) of the single-tank system. We have made no attempt to evaluate the ramifications of the aspect ratios that result from this parameter sensitivity on other parameters or on manufacturing or production. The system capacitance effects for the single-tank system are shown in Figure 4-3. An optimum in Q_{NET} occurs at around 400 kJ/°C (211 Btu/°F), the same as for the multiple-tank system.

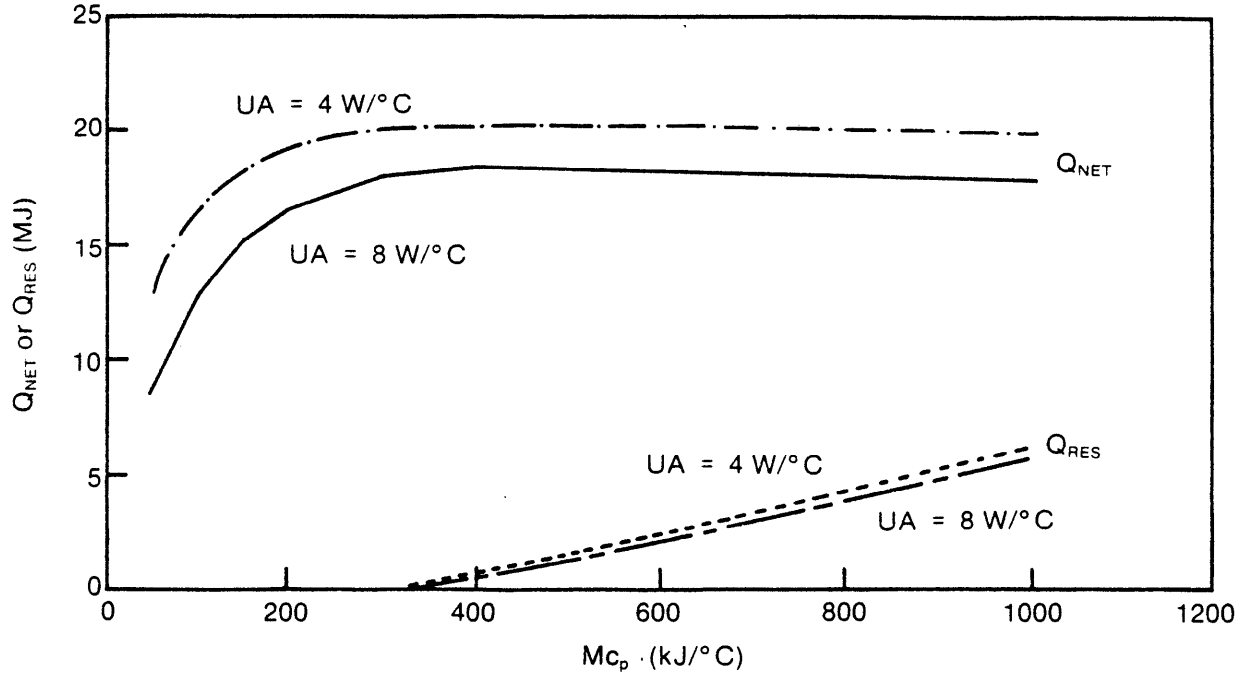

Figure 4-2. Effect of Capacitance on Predicted SRCC Test Performance for the Multiple-Tank (ICS #1) System (optical efficiency = 0.7)

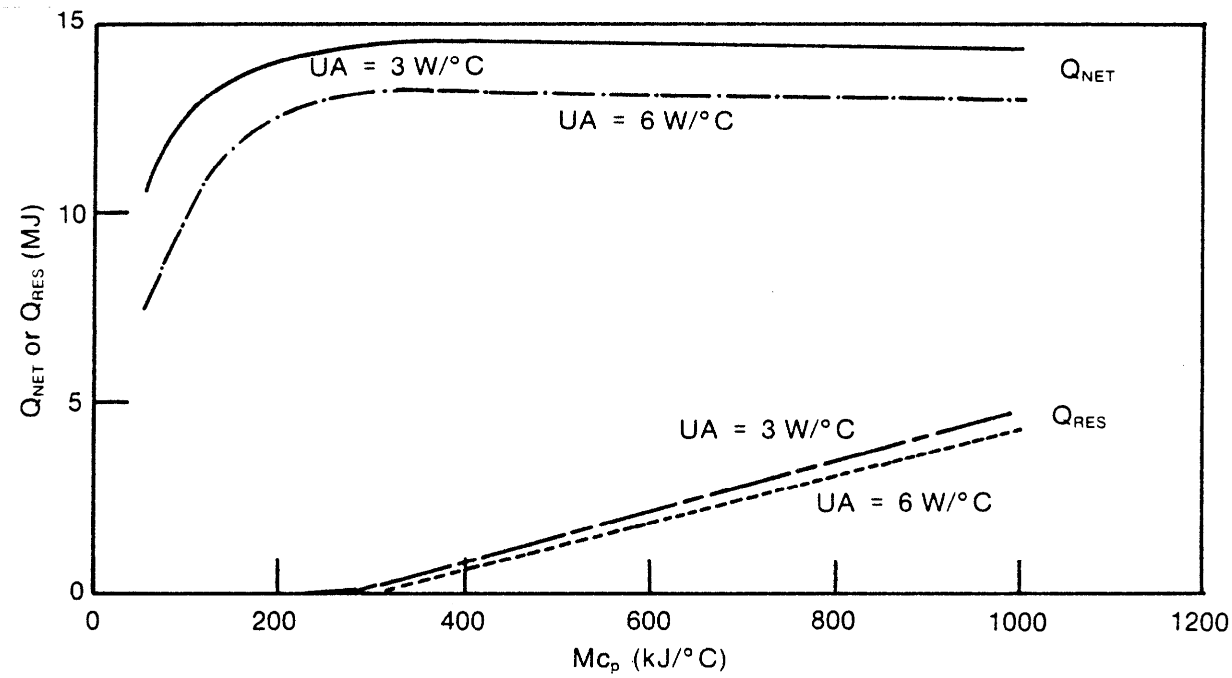

Figure 4-3. Effect of Capacitance on Predicted SRCC Test Performance for the Single-Tank (ICS #2) System (optical efficiency = 0.5)

For a continuous draw profile, it can be shown fairly simply that performance is not a function of system capacitance. The results discussed above show that for the SRCC draw profile, there is an optimum in performance at a certain capacitance [~400 kJ/°C (211 Btu/°F)]. It is clear then that draw profile has an effect on performance. The specific effects of capacitance on performance are not clear, so an optimum capacitance can not be determined. We did not explore the interrelated effects of aperture area, capacitance, and draw profile in this study. These effects must be understood for the system designer to properly conduct the design effort.

The effect of incident angle modifier changes, through B_0, is shown in Figure 4-4. As can be seen, very large changes in B_0 result in very small changes in both Q_{NET} and Q_{RES}.

Stratification has been accounted for in the multinode model by separating the ICS system into a number of fully mixed zones. Whenever flow (draw) occurs in the system, stratification is enhanced and performance is improved as hotter water is delivered to the load. The effects of increasing the number of nodes modeled for ICS #1 and ICS #2 are shown in Figures 4-5 and 4-6, respectively. It is clear that the initial increase of nodes over a single, fully mixed tank results in fairly significant improvement in Q_{NET} and a decrease in Q_{RES} and thus does compare with the expected effects of actual tank stratification. Beyond 8 or 10 nodes, the change in performance is slight. This agrees with the findings of Zollner (1984).

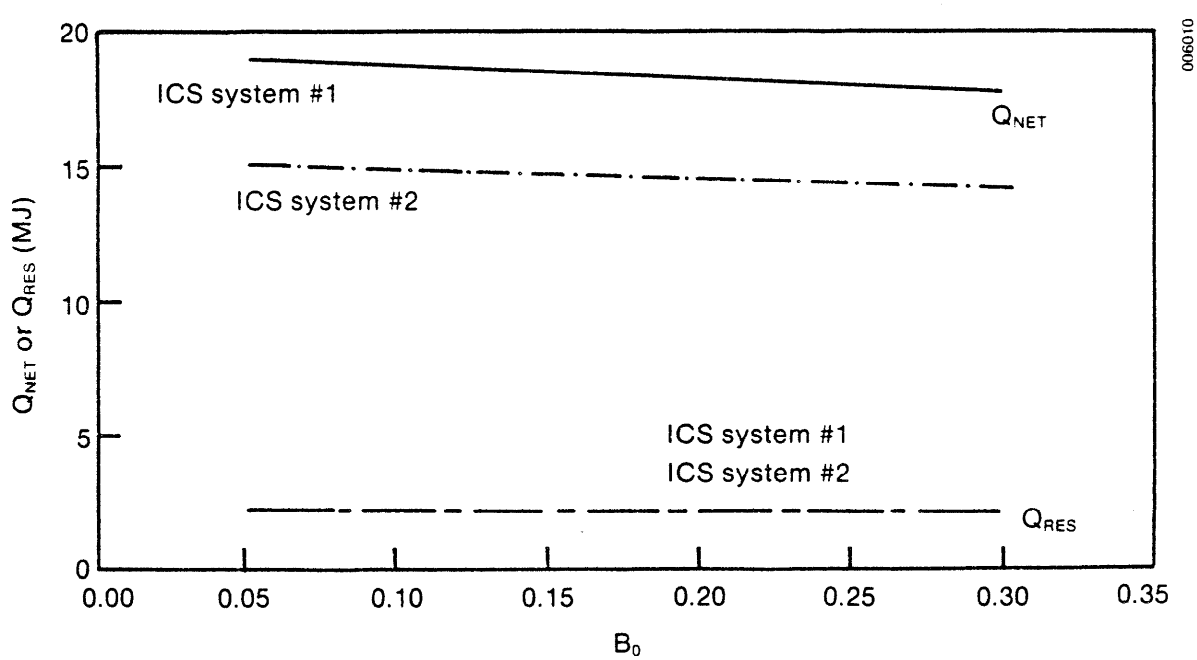

Figure 4-4. Effect of B_0, the Incident Angle Modifier, on Predicted SRCC Test Performance

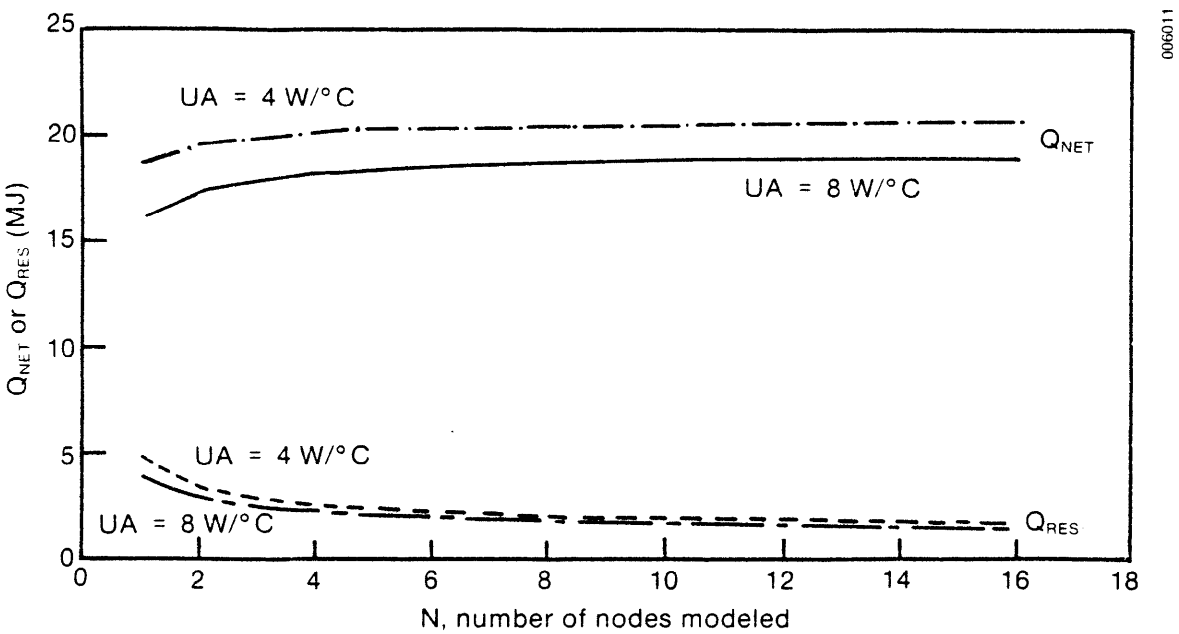

Figure 4-5. Effect of Number of Nodes on Predicted SRCC Test Performance for the Multiple-Tank (ICS #1) System (optical efficiency = 0.7)

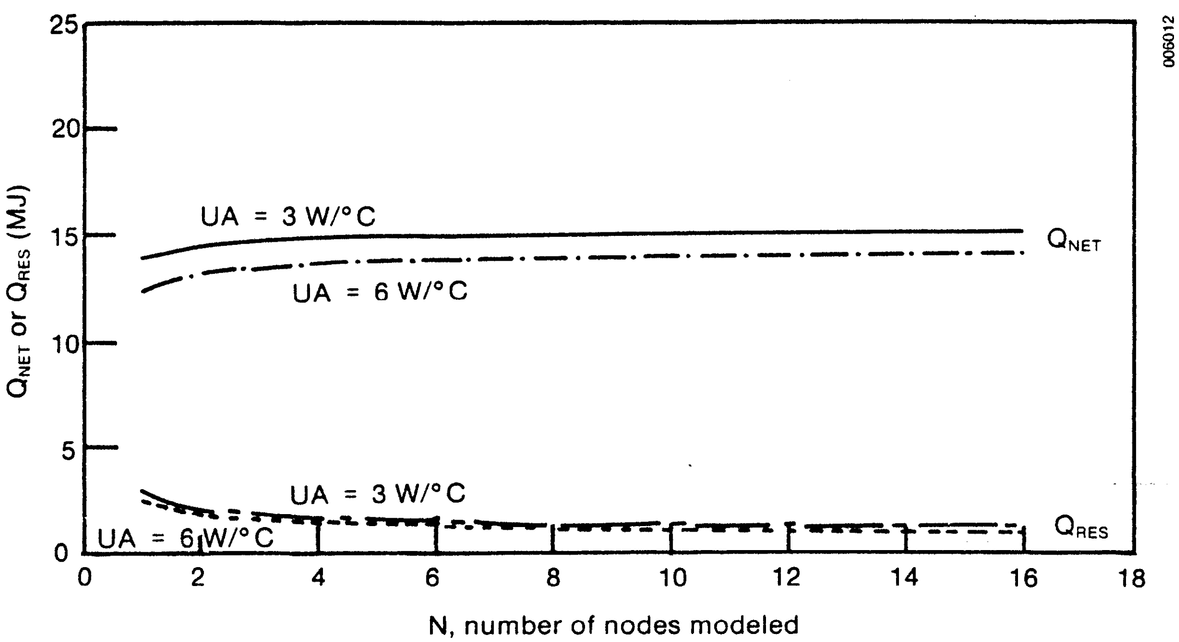

Figure 4-6. Effect of Number of Nodes on Predicted SRCC Test Performance for the Single-Tank (ICS #2) System (optical efficiency = 0.5)

4.3.2 Comparison with Test Results

We also employed the model to see if actual ICS system test results could be duplicated for several units on the market. Known parameters for these systems included the net aperture area, the fluid capacity, the absorber and glazing types, and, of course, the published test results. We used the capacitance of the tank fluid as the system capacitance in the model. The published heat loss coefficient was used without modification. Given the number of glazings and the system configuration, we assigned a value for B_0.

The only remaining parameters are the η_0 and the number of nodes. For a multiple-tank system, we used the number of tanks as the number of nodes, since each tank tends to be small and may be considered fully mixed. For a single-tank system, the choice of nodes was not so simple. Since some stratification is bound to exist, we started with an assumption of 2 nodes for each unit in the system. This leaves only the η_0 to be adjusted. Table 4-2 lists the ICS systems we modeled along with some of the important design features and test results from SRCC (1983). The Cornell 360 was chosen because a detailed model of this single-tank unit has been developed by Lindsay and Thomas (1983), and we plan to use their model in subsequent work. The Cornell 480 represents a unit with very low heat losses compared with others tested and was interesting from that standpoint alone. The Gulf Thermal PT40 is representative of the multiple-tank designs and has been modeled in some detail by Cummings (1983). The table shows, in addition to the published test results, the test results normalized by net aperture area. This makes performance comparisons somewhat more straightforward.

Generally, it was quite easy to match the Q_{NET} values within 3% for all the units by adjusting η_0 primarily and the number of nodes secondarily. However, the resulting comparison for Q_{RES} was not as successful. When a product had been tested as both a one- and two-unit system, we attempted to adjust the parameters for the one-unit results and then use those parameters for the two-unit test result comparison. The opposite sequence was also tried. The results of both these sequences for systems tested with both one and two units were very similar. Table 4-3 gives the resulting parameters for the five sets of test results.

To establish the validity of these parameters for each of these systems, longer-term experimental test data would have to be obtained and the model exercised against the environmental inputs and draw characteristics of the test. In the meantime, the technique of estimating the ICS performance parameters based on the multinode model seems reasonably adequate for estimates of SRCC system tests results for Q_{NET}.

4.3.3 Miscellaneous Studies

We can use the multinode model and the SRCC test simulation to look at other issues as well as parameter sensitivities and comparisons with test data. One

Table 4-2. System Description and SRCC 200-82 Test Results for Several Commercial ICS Systems

System	Cornell Energy 360	Cornell Energy 480-1	Cornell Energy 480-2	Gulf Thermal PT40-N	Gulf Thermal PT40-2
Number of units	2	1	2	1	2
Gross area [m^2 (ft^2)]	3.36 (36.2)	2.2 (23.7)	4.4 (47.3)	1.81 (19.5)	3.62 (39.0)
Net area [m^2 (ft^2)]	3.16 (34.0)	2.0 (21.5)	4.0 (43.0)	1.62 (17.4)	3.24 (34.9)
Fluid capacity [m^3 (gal)]	0.24 (63.4)	0.16 (42)	0.32 (85)	0.15 (40)	0.29 (80)
Fluid Mc_p [kJ/°C (Btu/°F)]	1006.00 (530)	662 (349)	1,324 (697)	629 (331)	1,215 (640)
Tank type	glass-lined	glass-lined	glass-lined	stainless steel	stainless steel
steel	steel	steel			
Absorber surface	nickel foil coating	selective surface	selective surface	black nickel	selective paint
Reflector surface	reflective polyisocyanurate	aluminized parabolic	aluminized parabolic	N/A	N/A
Number of glazings	3	2	2	3	3
Glazing type:					
1	low iron tempered glass	low iron glass	low iron glass	low iron glass	low iron glass
2	reinforced fiberglass	low iron glass	low iron glass	Teflon	Teflon
3	reinforced fiberglass acrylic	--	--	Teflon	Teflon
SRCC 200-82 test data:					
Q_{NET} [kJ (Btu)]	20,996 (19,905)	16,000 (15,169)	30,300 (28,726)	15,298 (14,503)	25,954 (24,606)
Q_{NET}/area [kJ/m^2 (Btu/ft^2)]	6,644 (585)	8,000 (705)	7,575 (667)	9,443 (832)	8,010 (706)
Q_{RES} [kJ (Btu)]	6,183 (5,862)	750 (711)	10,700 (10,144)	949 (900)	12,871 (12,202)
Q_{RES}/area [kJ/m^2 (Btu/ft^2)]	1,957 (172)	375 (33.0)	2,675 (236)	586 (51.6)	3,973 (350)
L [W/°C (Btu/h °F)]	10.44 (19.8)	3.01 (5.71)	5.72 (10.9)	6.31 (12.0)	14.2 (26.9)
U [W/m^2 °C (Btu/h ft^2 °F)]	3.3 (0.58)	1.51 (0.27)	1.43 (0.25)	3.89 (0.69)	4.38 (0.77)

Table 4-3. Comparison of Model and SRCC Test Results for Selected Commercial ICS Systems

System	Number of Units	Mc_p [kJ/°C (Btu/°F)]	Net Area [m^2 (ft^2)]	UA [W/°C (Btu/h °F)]	η_o	B_O	Number of Nodes	Q_{NET} [kJ (Btu)] Model	Q_{NET} [kJ (Btu)] SRCC	Q_{RES} [kJ (Btu)] Model	Q_{RES} [kJ (Btu)] SRCC
Cornell 360	2	1,006 (530)	3.16 (34)	10.4 (20)	0.55	0.23	8	21,084 (19,989)	20,996 (19,905)	6,695 (6,347)	6,183 (5,862)
Cornell 480	1	660 (348)	2.0 (22)	3.0 (5.7)	0.55	0.20	4	16,207 (15,365)	16,000 (15,169)	2,296 (2,177)	750 (711)
Cornell 480	2	1,320 (695)	4.0 (43)	5.7 (10.8)	0.55	0.20	4	30,052 (28,491)	30,300 (28,726)	13,780 (13,064)	10,700 (10,144)
PT40-N	1	606 (319)	1.62 (17)	6.3 (11.9)	0.705	0.23	4	15,323 (14,527)	15,298 (14,503)	1,756 (1,665)	949 (900)
PT40-2	2	1,212 (638)	3.24 (35)	14.2 (26.9)	0.705	0.23	8	25,172 (23,864)	25,954 (24,606)	11,230 (10,647)	12,871 (12,202)

important issue with ICS systems is overnight losses, discussed in Section 2.2.3. We used the model to look at how overnight losses are affected by both the system mass and heat loss coefficient.

To calculate overnight losses, we allowed the system simulation to reach steady-state daily operation using the SRCC 200-82 test conditions. To ensure steady state, the normal SRCC convergence requirement (solar fraction changing by less than 3%) was tightened considerably by simulating 10 days of operation. Overnight losses are defined here as system losses whenever there is no solar irradiance. For the SRCC solar irradiance profile, there are 9 hours of sunshine [17,028 kJ/m^2 (1,500 Btu/ft^2) total]. We used the ICS performance parameters for ICS #1 and ICS #2 from Table 4-1 for the baseline values. The mass of the system and then the heat loss coefficient of each system were varied while all other parameters were held constant. For the simulations with varying mass, two different ambient temperatures were used: the standard value of 22°C and a lower value of 11°C (51.8°F). Results from these simulations are shown in Figure 4-7 for ICS #1 and Figure 4-8 for ICS #2.

It is obvious from Figures 4-7 and 4-8 that increasing the system mass also increases the overnight loss. The loss increases rapidly for low mass systems and begins to level out at higher mass. Note that the baseline mass is slightly less than 100 kg (220 lb) for a 2.0-m^2 (21.5-ft^2) aperture and results in near maximum Q_{NET}. For ICS #1, shown in Figure 4-7, the 100-kg system has overnight losses that are almost 6% of the incident energy and 11% of Q_{NET}. If a cooler environment is assumed [e.g., 11°C (51.8°F) ambient],

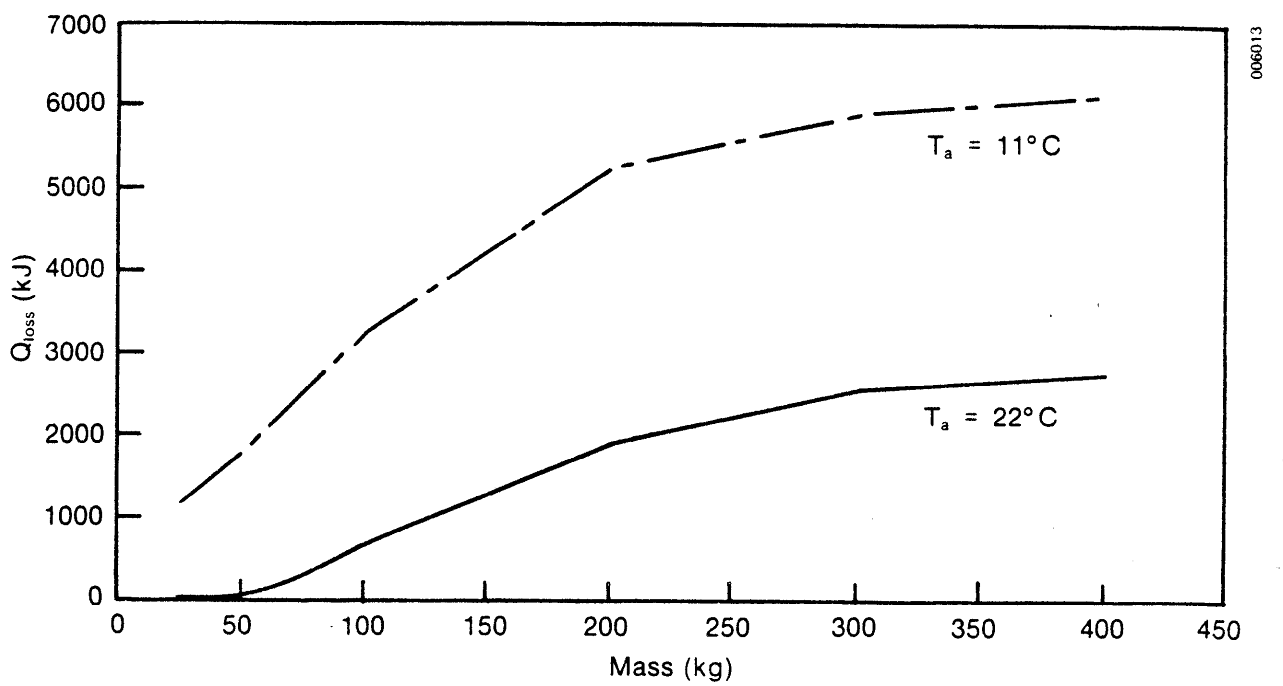

Figure 4-7. Overnight Losses for ICS System #1 under SRCC Test Conditions as a Function of System Mass

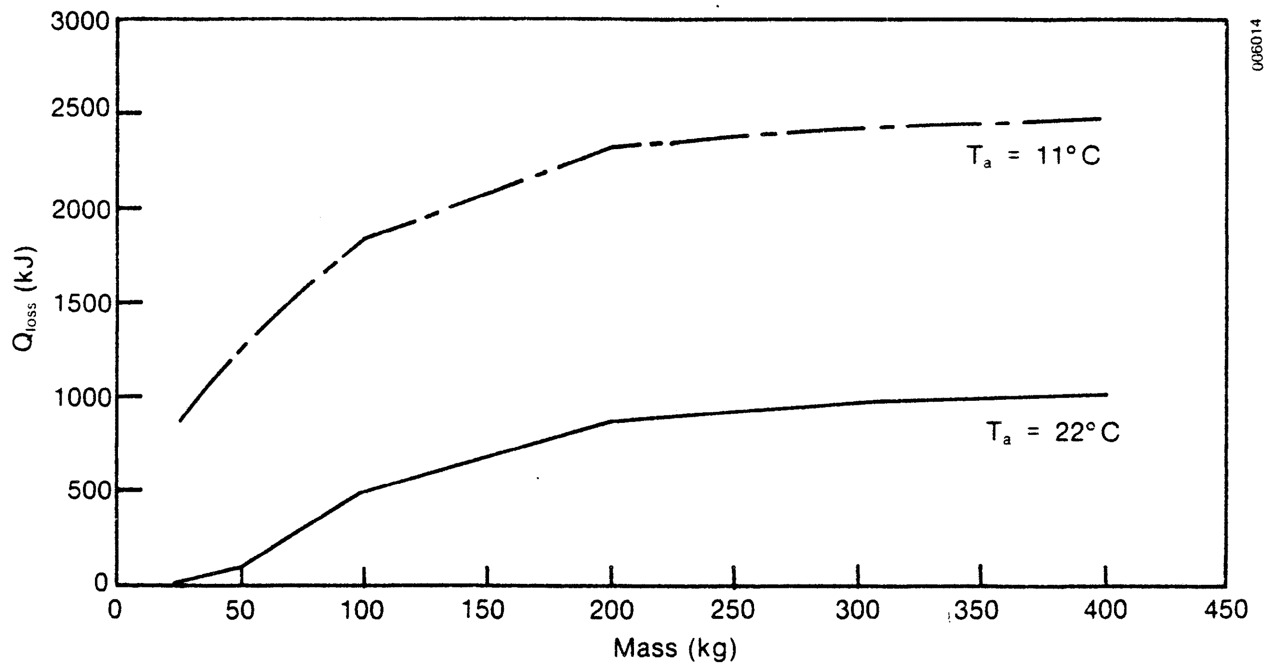

Figure 4-8. Overnight Losses for ICS #2 under SRCC Test Conditions as a Function of System Mass

then a 100-kg (220-lb) system has overnight losses that are almost 10% of the incident and almost 25% of Q_{NET}. Those values increase to almost 16% of incident and over 43% of Q_{NET} for a 200-kg system. This shows the relative importance of keeping the mass at a minimum level in cooler environments, although the possibility of freezing should be considered. ICS #2 shows the same trends, although at lower levels because of the lower heat loss coefficient [1.5 W/m^2 °C (0.26 Btu/h ft^2 °F)] compared with 4.0 W/m^2 °C (0.7 Btu/h ft^2 °F) for ICS #1]. A 100-kg system at 22°C (71.6°F) ambient has overnight losses that are 1.5% of incident and 3.4% of Q_{NET}. Figure 4-8 shows the overnight loss for ICS #2 at both 22°C (71.6°F) and 11°C (51.8°F) ambient temperature.

The effect of varying the loss coefficient on overnight losses for ICS #1 and ICS #2 was determined with the ambient temperature at 22°C (71.6°F) only. These results are shown in Figure 4-9. The overnight losses for both systems over the range of loss coefficients evaluated change from <1% to <3% of the incident energy. It appears then that overnight losses (at least in warmer climates) represent relatively small fractions of the total system losses for reasonable design values of system mass. For cooler and cold environments, this may not be true.

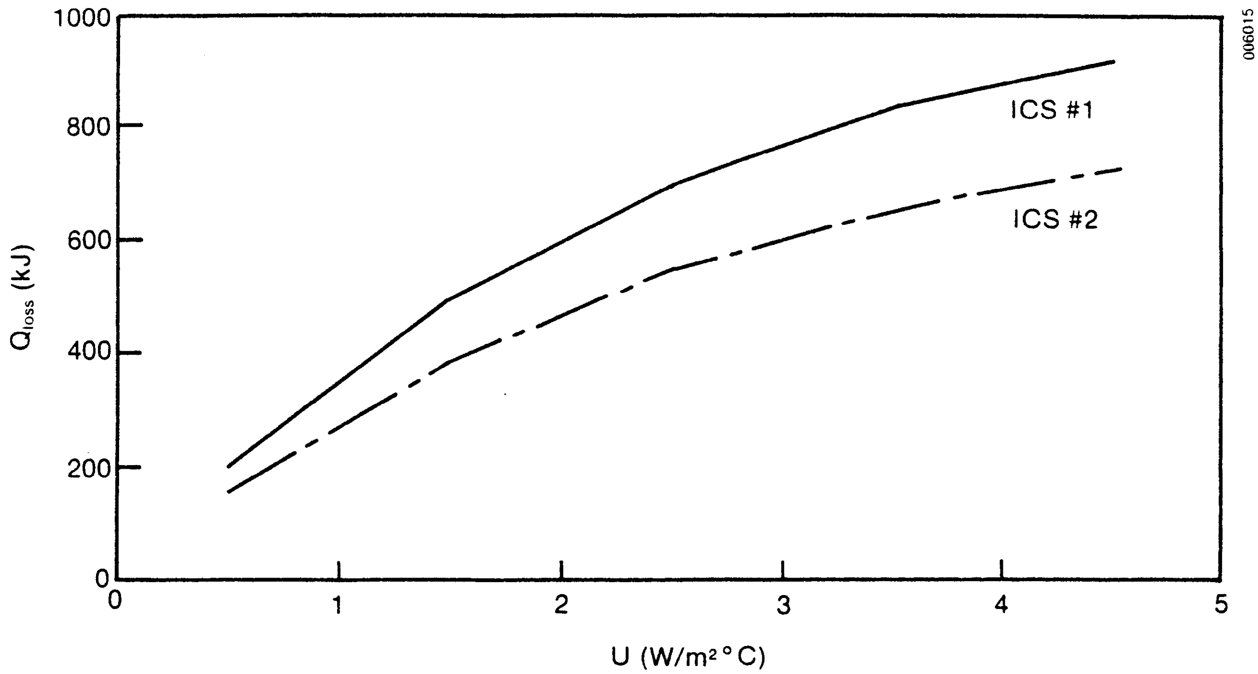

Figure 4-9. Overnight Losses for ICS #1 and #2 under SRCC Test Conditions as a Function of Loss Coefficient, at T_a = 22°C

SECTION 5.0

ANNUAL PERFORMANCE SIMULATION OF ICS SYSTEMS

The annual thermal performance of a solar energy system can be analyzed at various levels of complexity. Our approach has been to begin with simplified design tools to bracket the range of expected performance, using a code that requires minimal computer time so that low-cost parametric analyses are possible. This first step identifies components of the system that have the greatest uncertainty in behavior or the greatest potential for improvement. From the results of the parametric study, one can reasonably assess specific design or operational issues in sufficient detail to answer remaining performance questions.

5.1 UNIVERSITY OF WISCONSIN DESIGN METHOD

Zollner (1985) developed a simple annual performance algorithm for ICS systems that compares well with TRNSYS simulations (Klein 1983) using the same performance and load characteristics. The model is applicable to most commercially available ICS systems because it uses generic performance indices (U_L, a loss coefficient, and $\bar{\eta}_o$, average optical efficiency) that are not configuration-dependent. The performance parameters can be found analytically or experimentally for the system under consideration. Assumptions include a fully mixed tank, negligible change in internal energy during a month, and a continuous draw of hot water to satisfy the load. Required inputs are monthly average values of incident radiation in the plane of the ICS system, ambient temperature, sky temperature, cold water supply temperature, glazing area, loss coefficient, and average optical efficiency. The model calculates the monthly average draw temperature and solar fraction. Details of the method are described below.

An energy balance on the ICS system may be written

$$0 \approx (\bar{H}_T n)\, A_c(\bar{\eta}_o) - U_L A_c \Delta\theta(\bar{T}_t - \bar{T}_a) - M_D c_p(\bar{T}_D - \bar{T}_m) \,, \qquad (5\text{-}1)$$

where

H_T = the daily average incident radiation in the plane of the glazing (kJ/m^2 day)

n = the number of days in the month (days)

A_c = the collection area of the ICS system (m^2)

η_o = the monthly average optical efficiency

U_L = the loss coefficient (W/m^2 ^oC)

$\Delta\theta$ = the amount of time in the month (s)

$\bar{T}_t$ = the average tank temperature (^oC)

$\bar{T}_a$ = the monthly ambient temperature (^oC)

M_D = the mass of water withdrawn for the load during the month (kg)

c_p = the specific heat of water (kJ/kg °C)
$\overline{T}_D$ = the average draw temperature (°C)
$\overline{T}_m$ = the mains water temperature (°C).

From the assumption of continuous draw and no stratification, we may equate the monthly average draw temperature to the average tank temperature; i.e., $\overline{T}_D = \overline{T}_t$. Solving for the draw temperature, we obtain

$$\overline{T}_D = \frac{\overline{H}_T n A_c (\overline{\tau\alpha}_o) + M_D c_p \overline{T}_m + U_L A_c \Delta\theta \overline{T}_a}{M_D c_p + U_L A_c \Delta\theta} \ . \tag{5-2}$$

The load is simply the energy required to heat the monthly draw volume from the cold water supply temperature to the set-point temperature. From this definition of load, we may calculate the solar fraction for the fully mixed tank $f_{m,c}$ as

$$f_{m,c} \ \frac{M_D c_p (\overline{T}_D - \overline{T}_m)}{M_D c_p (T_S - \overline{T}_m)} \ , \tag{5-3}$$

where T_S is the set temperature of the auxiliary tank. Zollner (1984) reports excellent agreement between this model and TRNSYS simulations that use the same assumptions of continuous draw, fully mixed tank, and system performance parameters of U_L and $\overline{\tau\alpha}_o$ rather than more specific system characteristics. He also observed good agreement with TRNSYS simulations that used other draw profiles, as long as the draws were not taken either completely in the morning or completely in the evening.

In his TRNSYS runs, Zollner also studied performance assuming a stratified tank as well as one that was fully mixed. He used a simplified stratification model that neglects heat transfer between nodes except when a draw is taken. Stratification in the model occurs because cooler mains temperature water is introduced into the tank during a draw. The degree to which stratification improves performance is a function of the ratio of load volume to tank volume, termed "tank turnover." Based on the TRNSYS simulations, an expression was developed that incorporates stratification into the simple method and calculates a modified solar fraction:

$$\frac{f_{s,c}}{f_{m,c}} = 1 + \frac{0.326}{TT} (1 - f_{m,c}) \ . \tag{5-4}$$

Here, $f_{s,c}$ is the solar fraction provided by the ICS system assuming stratification. Zollner found this equation to hold for loss coefficients from 1.9 to 4.4 W/m °C (0.33-0.77 Btu/h ft^2 °F), tank volumes from 130 to 250 L (34-66 gal), average optical efficiencies from 0.39 to 0.69, and ratios of tank volume to area of 47 to 91 L/m^2 (1.2-2.2 gal/ft^2).

The SRCC test procedure used to determine the loss coefficient does not account for additional losses that would occur in an installed system radiating to the sky. To correct for a sky temperature below the ambient, Zollner defined an effective sink temperature $\overline{T}_e$ that accounts for both convective and radiative losses. He suggests subtracting a value of one-fourth of the monthly average sky temperature depression from the monthly average ambient temperature to obtain a value for $\overline{T}_e$ to replace $\overline{T}_a$ in Eq. 5-2.

5.2 ANNUAL PERFORMANCE OF ICS SYSTEMS

To examine the annual thermal performance of ICS systems and investigate the potential for design improvements, we developed an interactive computer model using the algorithm presented in the previous section. The program allows the user to select one of three sites, chosen to represent a range of climates, including two in which freezing temperatures occur regularly (Denver, Madison, and Phoenix); the area of the ICS system; the loss coefficient; the average optical efficiency; the daily hot water draw; and whether or not stratification is modeled. The site-specific data included in the code for each of the three sites are the monthly average incident radiation on a surface tilted at latitude and monthly averages for ambient, cold water supply, and sky temperatures. Monthly average site information for the three cities used in our analyses may be found in Tables 5-1 through 5-3.

Table 5-1. Monthly Average Meteorological Data for Denver

Month	Ambient Temperature		Sky Temperature		Mains Temperature		Incident Radiation on a Surface Tilted at Latitude	
	(°C)	(°F)	(°C)	(°F)	(°C)	(°F)	(MJ/m²)	(Btu/ft²)
Jan.	0.0	32.0	19	66	3.9	39.0	530	46,670
Feb.	0.0	32.0	19	66	4.4	39.9	530	46,670
Mar.	3.0	37.4	19	66	6.1	43.0	660	58,100
Apr.	9.0	48.2	18	64	9.4	48.9	660	58,100
May	14.0	57.2	16	61	12.8	55.0	690	60,750
June	19.0	66.2	16	61	15.6	60.1	700	61,640
July	23.0	73.4	15	59	17.2	63.0	720	63,400
Aug.	22.9	71.6	14	57	17.8	64.0	700	61,640
Sept.	17.0	62.6	17	63	17.2	63.0	670	59,000
Oct.	11.0	51.8	20	68	13.3	55.9	640	56,350
Nov.	4.0	39.2	18	64	7.2	45.0	500	44,030
Dec.	0.0	32.0	20	68	2.8	37.0	480	42,260

Table 5-2. Monthly Average Meteorological Data for Phoenix

Month	Ambient Temperature (°C)	Ambient Temperature (°F)	Sky Temperature (°C)	Sky Temperature (°F)	Mains Temperature (°C)	Mains Temperature (°F)	Incident Radiation on a Surface Tilted at Latitude (MJ/m^2)	Incident Radiation on a Surface Tilted at Latitude (Btu/ft^2)
Jan.	10.7	51.3	20	68	8.9	48.0	540	47,550
Feb.	12.8	55.0	22	72	8.9	48.0	580	51,070
Mar.	15.4	59.7	22	72	10.0	50.0	740	65,160
Apr.	19.8	67.6	22	72	11.1	52.0	810	71,320
May	24.6	76.3	22	72	13.9	57.0	810	71,320
June	29.2	84.6	21	70	15.0	59.0	820	72,200
July	32.9	91.2	14	57	17.2	63.0	780	68,680
Aug.	31.7	89.1	14	57	23.9	75.0	780	68,680
Sept.	28.8	83.8	17	63	26.1	79.0	750	66,040
Oct.	22.3	72.1	21	70	20.6	68.1	710	62,520
Nov.	15.4	59.7	20	68	15.0	59.0	580	51,070
Dec.	11.4	52.5	20	68	12.2	54.0	520	45,790

Table 5-3. Monthly Average Meteorological Data for Madison

Month	Ambient Temperature (°C)	Ambient Temperature (°F)	Sky Temperature (°C)	Sky Temperature (°F)	Mains Temperature (°C)	Mains Temperature (°F)	Incident Radiation on a Surface Tilted at Latitude (MJ/m^2)	Incident Radiation on a Surface Tilted at Latitude (Btu/ft^2)
Jan.	-8.4	16.9	14	57	7.2	45.0	330	29,060
Feb.	-6.5	20.3	12	54	7.2	45.0	390	34,340
Mar.	-1.0	30.2	14	57	7.2	45.0	490	43,140
Apr.	7.4	45.3	12	54	7.2	45.0	490	43,140
May	13.3	55.9	11	52	7.2	45.0	570	50,190
June	18.8	65.8	9	48	7.2	45.0	580	51,070
July	21.2	70.2	10	50	7.2	45.0	610	53,710
Aug.	20.4	68.7	10	50	7.2	45.0	590	51,950
Sept.	15.4	59.7	11	52	7.2	45.0	510	44,900
Oct.	9.9	4.8	12	54	7.2	45.0	450	39,620
Nov.	1.5	34.7	11	52	7.2	45.0	290	25,530
Dec.	-5.6	21.9	11	52	7.2	45.0	260	22,890

From our manufacturers' survey, we found that the average net glazing area for an ICS system was about 3 m^2 (32.3 ft^2). However, for a parametric analysis, we chose a smaller size so that even under the best possible conditions (for example, a system in Phoenix with a very high optical efficiency and a very low loss coefficient), the system never produces surplus energy for a hot water draw typical of a four-person household. The ICS performance algorithm is not based on previous history; i.e., it cannot model carry-over of excess energy from one month to the next. We found that an area of 1.7 m^2 (18.3 ft^2) tilted at a slope equal to the latitude never produced excess energy for a load of 300 L/day (79.3 gal/day) at a 50°C (122°F) set-point temperature, even under the most favorable circumstances that we chose to model, so this area was used in each of the foregoing analyses. Because of the uncertainty in the model's ability to predict actual stratification behavior precisely, our comparisons do not assume stratification. Throughout this study, we assumed a hot water set-point temperature of 50°C and a hot water usage rate of 300 L/day year-round. The load is modeled as if it were extracted on a continual basis, but Zollner (1984) has shown that these predictions may be reasonably extended to the RAND profile or another profile that is not heavily weighted toward either morning or evening draw.

Our first step was to assess the performance of a base-case system in each of the selected sites, varying first the heat loss coefficient and then the optical efficiency. Figures 5-1 and 5-2 contain the results of these parametric analyses. Figure 5-1 shows variation in performance as a function of heat loss coefficient for a system with an optical efficiency of 0.6. In commercially available systems, the value of loss coefficient ranges from a high of 4.8 W/m^2 °C (0.85 Btu/h ft^2 °F) to a low of 1.43 W/m^2 °C (0.25 Btu/h ft^2 °F). Over this range the annual delivered energy for Denver increases approximately 40% as the loss coefficient decreases. Improvements for Madison and Phoenix are somewhat less, around 25%, as evidenced by the shallower curves. Achieving these performance improvements in real systems depends on maintaining the optical characteristics of the ICS system while lowering the heat loss coefficient.

Next, we examined the effects of varying the optical efficiency while holding the heat loss coefficient constant at 1 W/m^2 °C (0.18 Btu/h ft^2 °F). These results appear in Figure 5-2. The optical efficiency is not specifically measured in the SRCC test, so it must be inferred as in Section 4.3.3. For available systems, optical efficiency ranges from approximately 0.5 to 0.73. As η_o increases toward 0.73, the annual delivered energy increases between 42% and 47% for the three cities under investigation. The combined effects of optical efficiency and loss coefficient are shown graphically in Figure 5-3. If we select a delivered energy of 5 GJ/yr (4.7 × 10^6 Btu/yr), we find that this load may be supplied in Denver by several combinations of performance indices. Combinations include: $\overline{\eta}_o$ = 0.5 and U_L = 1.5 W/m^2 °C (0.26 Btu/h ft^2 °F); $\overline{\eta}_o$ = 0.6 and U_L = 3.5 W/m^2 °C (0.62 Btu/h ft^2 °F); and $\overline{\eta}_o$ = 0.7 and U_L = 5.0 W/m^2 °C (0.88 Btu/h ft^2 °F). Therefore, though it may be easier to add thermal resistance to decrease the heat loss coefficient, it is important to maintain a good optical efficiency for an ICS system, as performance is significantly reduced with even a small change in $\overline{\eta}_o$.

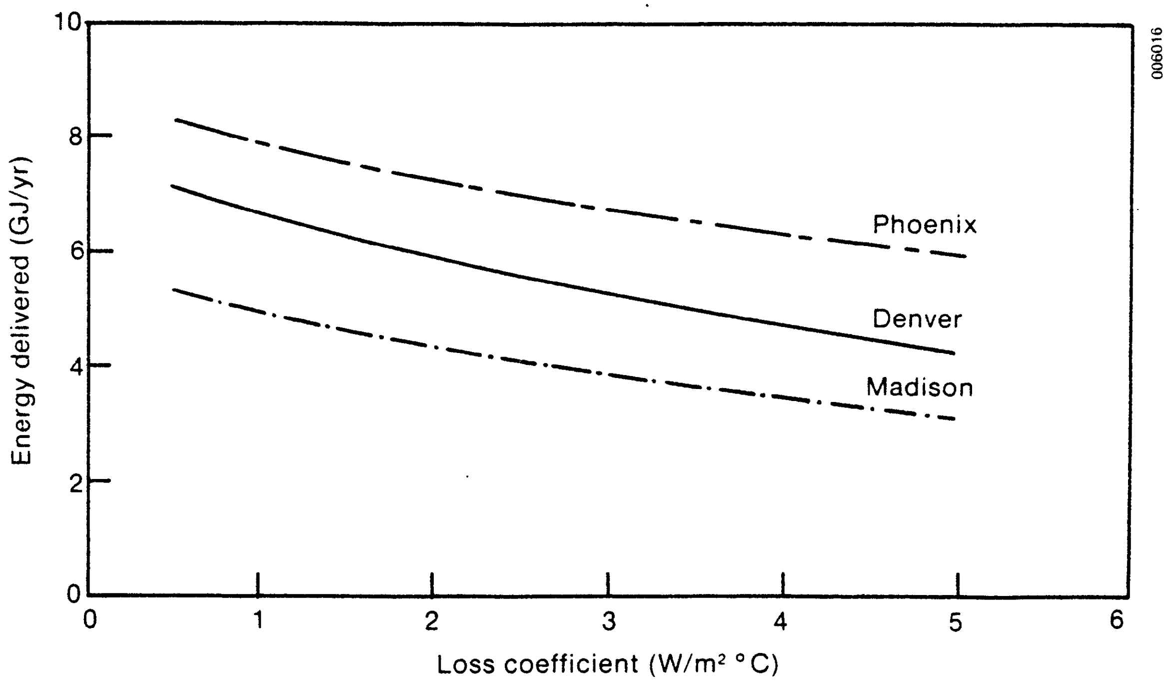

Figure 5-1. ICS System Annual Performance as a Function of Loss Coefficient in Denver, Madison, and Phoenix (area = 1.7 m^2, optical efficiency = 0.6)

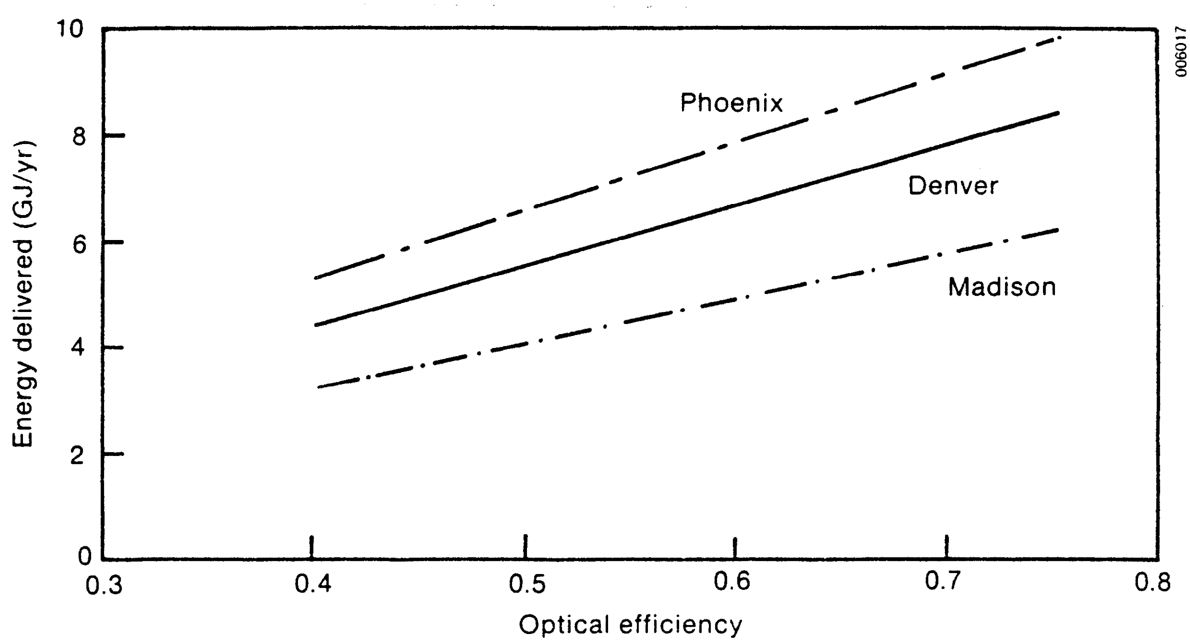

Figure 5-2. ICS System Annual Performance as a Function of Optical Efficiency in Denver, Madison, and Phoenix (area = 1.7 m^2, U_L = 1.0 W/m^2 °C)

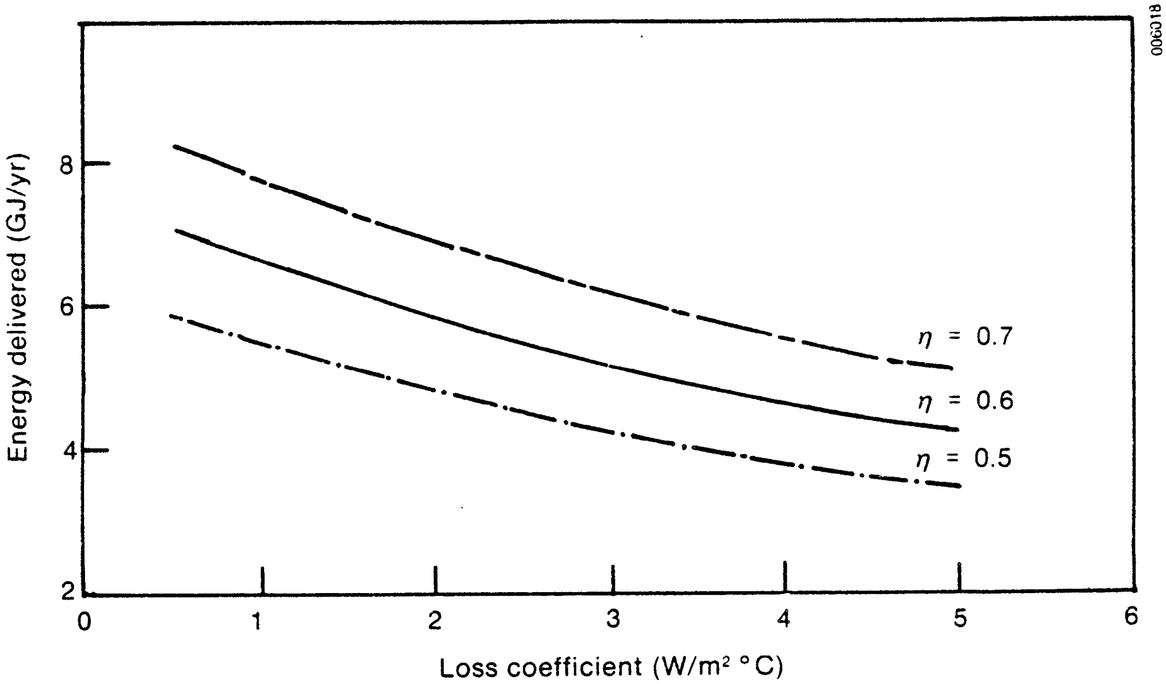

Figure 5-3. Combined Effects on ICS System Annual Performance in Denver of Loss Coefficient and Optical Efficiency (area = 1.7 m^2)

5.3 COMPARISON WITH DRAINBACK SYSTEMS

Because the primary contender for low-cost SDHW supply is the drainback system, we compared performance of the ICS system described above to the low-cost drainback system investigated in our previous work. We also looked at the comparison between the low-cost system and commercially available drainback systems, and examined behavior as a function of performance indices as we have done with ICS systems. For the drainback systems, we used F-CHART (Klein et al. 1983) configured as described in Section 2.3. We varied the heat loss coefficient $F_R U_L$ and looked at two values of optical efficiency: one corresponded to the ICS system, 0.6, and one was typical of a commercially available high-performance flat-plate collector, 0.77. Results appear in Figure 5-4 for both the ICS and drainback systems operating in Denver. The curve of performance as a function of loss coefficient is significantly flatter for the drainback systems as predicted by F-CHART than for the ICS systems, indicating that fewer benefits accrue for drainback systems by improving their collector heat loss characteristics. This result is probably due to the impact of outdoor nighttime heat losses on ICS system performance. For the same optical efficiency and system size, the ICS will outperform the drainback for loss coefficients below approximately 1.6 W/m^2 °C (0.28 Btu/h ft^2 °F). However, most commercially available flat-plate collectors have greater optical efficiencies than those typically found in ICS systems.

Since systems with aperture areas of only 1.7 m^2 represent a fairly small solar fraction in Denver [e.g., the ICS in Figure 5-4 with U_L = 5 W/m^2 °C (0.88 Btu/h ft^2 °F) has a solar fraction of 0.22], we also compared these systems with aperture areas of 3.0 m^2 (32.3 ft^2). The results are shown in Figure 5-5. The energy delivery is, as expected, greater than that of the

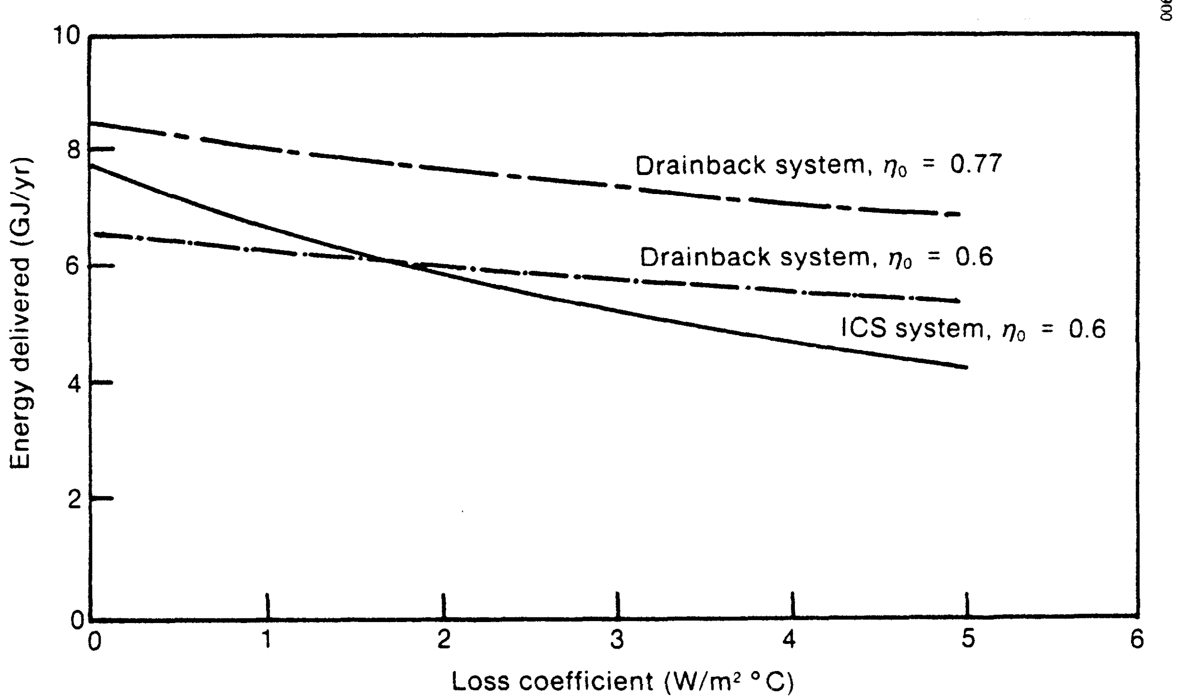

Figure 5-4. Comparison of ICS and Drainback System Annual Performance in Denver for Systems with an Aperture Area of 1.7 m^2

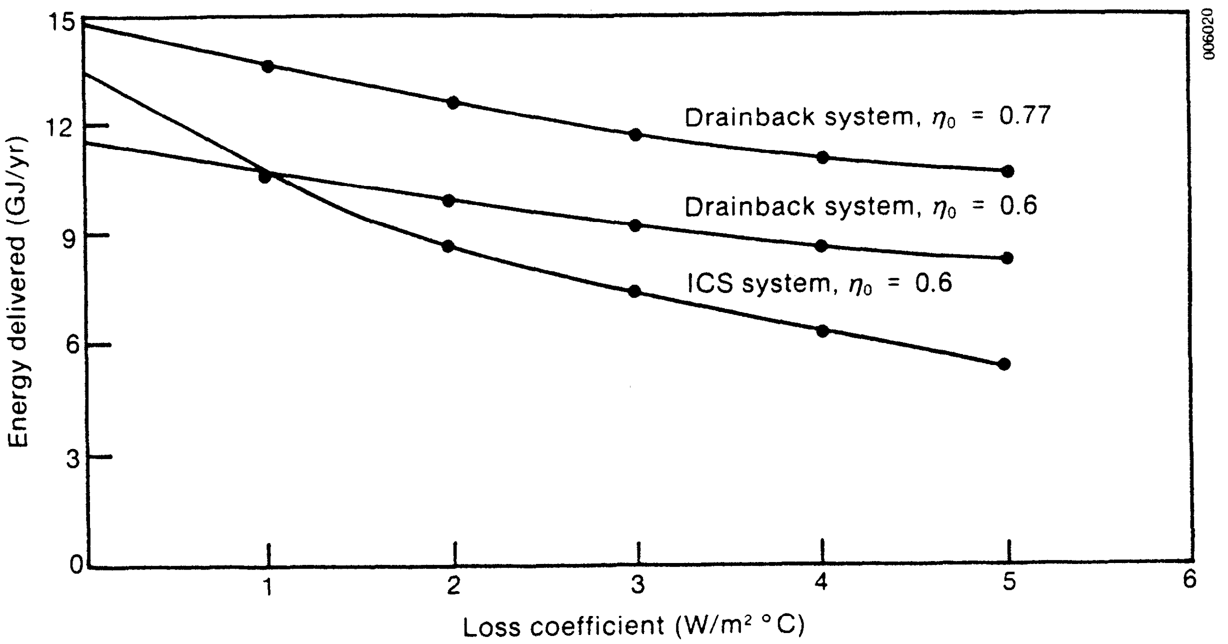

Figure 5-5. Comparison of ICS and Drainback System Annual Performance in Denver for Systems with an Aperture Area of 3.0 m^2

smaller systems, now with solar fractions about 50% greater [e.g., ICS with U_L = 5 W/m^2 ^oC (0.88 Btu/h ft^2 ^oF) has a solar fraction of 0.31 and the drainback with $\bar{\eta}_o$ = 0.77 and F_RU_L = 5 W/m^2 ^oC (0.88 Btu/h ft^2 ^oF) has a solar fraction of 0.59]. Larger systems also seem to favor the drainback for performance; i.e., a lower loss coefficient is required for the ICS system to outperform a drainback with the same $\bar{\eta}_o$, compared with the smaller [1.7-m^2 (18.3-ft^2)] systems. This is probably due to the increased overnight losses in the larger ICS system as the average tank temperature goes up for the same load.

SECTION 6.0

ECONOMIC ANALYSIS

This section combines the results of the installed cost estimates, life-cycle costs for repair and replacement, and the annual performance estimates into a discounted payback analysis.

The drainback data are for two different systems. One is the low-cost, low-performance system that uses a low-cost plastic collector with relatively low performance characteristics. The other is a commercial system that uses a high-performance collector and other off-the-shelf hardware currently available. Performance of these systems was estimated for Phoenix, Denver, and Madison using F-CHART. Detailed performance parameters used for those drainback systems can be found in Section 2.3.

Performance parameters for the ICS system are from Section 4.0, except for area. Although ICS #1 and ICS #2 do not differ significantly in performance, we chose to present data for a 4-m^2 (43.0-ft^2) ICS #2 system for the economic analysis. The load for the ICS system is slightly higher because there is a monthly variation in mains temperature in the analysis compared with a constant mains temperature in the drainback system analysis.

Fuel costs were taken from a U.S. Department of Energy study (1983) (commonly referred to as NEPP-IV) of current costs and projected costs for the year 2000. No attempt was made to adjust system costs for the year 2000 to account for the possibility of lower-cost systems. Table 6-1 shows the fuel costs used for Phoenix, Denver, and Madison.

Table 6-1. Present and Projected Residential NEPP-IV Fuel Costs

Location	Fuel Cost [1984 \$/GJ[a] (1984 \$/10^6 Btu)]			
	Natural Gas[b]		Electricity	
	1984	2000	1984	2000
Phoenix	9.28 (9.79)	15.13 (15.96)	16.43 (17.33)	18.70 (19.72)
Denver	9.28 (9.79)	15.13 (15.96)	16.65 (17.56)	18.70 (19.72)
Madison	9.59 (10.12)	16.61 (17.52)	19.02 (20.06)	21.46 (22.64)

[a]Adjusted by inflation from 1982 (as given in NEPP-IV) to 1984 using a 5% inflation rate.
[b]Assumes a 60% combustion efficiency.

The performance and cost data for the drainback and ICS systems have been combined in a discounted payback analysis that takes into account fuel escalation rates and the value of alternative investments (through discount rate). We assumed tax credits were not available.

An expression for discounted payback with fuel escalation and discount rates that include inflation is

$$P = \frac{\log_{10}\left[\frac{C}{F}\,\frac{A-1}{A} + 1\right]}{\log_{10}A} , \tag{6-1}$$

where P = discounted payback period
C = system cost
F = first year fuel savings
A = (1 + G)/(1 + R)
G = fuel escalation rate
R = discount rate .

With Eq. 6-1, the discounted payback period is not particularly sensitive to the fuel escalation and discount rates if these rates are relatively close to each other. In fact, if they are equal, the expression reduces to a simple payback. We used a fuel escalation rate of 9%/yr for natural gas and 7% for electricity and a discount rate of 10%/yr. An assumed inflation rate of 6%/yr is included in both the fuel escalation and discount rates.

Discounted paybacks were calculated using initial system cost for the two drainback systems and the ICS #2 for Phoenix, Denver, and Madison. These results are shown in Table 6-2. If we assume that payback periods of about 5 years are acceptable for residential consumers, then none of the systems look very attractive. Present fuel costs yield no paybacks lower than 10 years. At current natural gas costs, paybacks for all systems range from almost 20 to over 30 years. Current electricity costs reduce payback about 50%. NEPP-IV projects dramatic increases in natural gas costs in the year 2000. These projected costs cause paybacks that approach, but do not exceed, the paybacks for electricity.

In all cases, for a given location, the commercial drainback system has the highest payback period and the ICS #2 has the next highest, slightly more than the low-cost drainback, which has the lowest payback.

The expected cost of component repair and replacements also can be incorporated into a discounted payback calculation. The resulting paybacks for 1984 electricity fuel costs for the low-cost drainback and ICS #2 are shown in Table 6-3. For Phoenix, the payback increases about 6 years for both systems; for Denver, about 8 years; and for Madison, about 10 years. It is clear that when the repair and replacement costs are included, the economic benefits of these SDHW systems are severely reduced.

An important comparison for the potential buyer can be made between the commercially available drainback and ICS systems. Both use hardware that is currently available and has been priced using the same assumptions. The low-cost drainback system, on the other hand, uses inexpensive components, many of

Table 6-2. Performance and Economic Analysis of Drainback and ICS Systems for DHW Heating Using Initial Cost Only
(Fuel escalation = 9% for natural gas; 7% for electricity; discount rate = 10%, fuel costs and real fuel escalation rates based on NEPP-IV; see Table 6-1)

	Q_u	Q_{del}	Q_{AUX}	f_{DHW}	Fuel Savings (1984 $)				Discounted Payback (yr)			
					Natural Gas		Electricity		Natural Gas		Electricity	
	(GJ) (10^6 Btu)	(GJ) (10^6 Btu)	(GJ) (10^6 Btu)		1984	2000	1984	2000	1984	2000	1984	2000
Phoenix [Q_{1d} = 16.0 GJ (15.2 × 10^6 Btu)]												
Commercial drainback	17.9 (17.0)	15.4 (14.6)	0.5 (0.5)	0.97	143	233	256	288	25.4	14.9	15.8	13.7
Low-cost drainback	15.5 (14.7)	13.7 (13.0)	2.3 (2.2)	0.86	127	207	228	256	17.2	10.2	10.3	9.0
ICS #2 (4.0 m^2)	12.5 (11.9)	12.5 (11.9)	3.5 (3.3)	0.78	116	189	208	234	18.6	11.0	11.2	9.7
Denver [Q_{1d} = 18.1 GJ (17.2 × 10^6 Btu)]												
Commercial drainback	17.1 (16.2)	15.5 (14.7)	2.6 (2.5)	0.86	144	235	258	290	25.2	14.7	15.6	13.5
Low-cost drainback	13.0 (12.3)	11.9 (11.3)	6.2 (5.9)	0.66	110	180	198	223	20.1	11.8	12.1	10.6
ICS #2 (4.0 m^2)	10.5 (10.0)	10.5 (10.0)	7.5 (7.1)	0.58	97	159	175	197	22.6	13.2	13.7	11.9
Madison [Q_{1d} = 19.6 GJ (18.6 × 10^6 Btu)]												
Commercial drainback	13.1 (12.4)	12.3 (11.7)	7.4 (7.0)	0.62	118	192	234	264	31.7	18.4	17.7	15.2
Low-cost drainback	10.0 (9.5)	9.5 (9.0)	10.1 (9.6)	0.48	91	148	181	204	24.8	14.6	13.5	11.7
ICS #2 (4.0 m^2)	8.1 (7.7)	8.1 (7.7)	11.6 (11.0)	0.41	78	126	154	174	28.9	17.0	16.1	13.8

Table 6-3. Discounted Paybacks for 1984 Electricity Fuel Costs when Life-Cycle Costs Are Included (all other parameters identical to Table 6-2)

Location/System	Discounted Payback (yr)	
	Initial Cost	Initial + Repairs/Replacements
Phoenix		
Commercial drainback	15.6	24.8
Low-cost drainback	10.3	18.1
ICS #2	11.2	18.6
Denver		
Commercial drainback	15.6	24.5
Low-cost drainback	12.1	22.7
ICS #2	13.7	23.6
Madison		
Commercial drainback	17.7	28.3
Low-cost drainback	13.5	25.7
ICS #2	16.1	28.4

which are not used in systems being installed today (e.g., unpressurized, low-cost tanks, polybutylene piping, plastic collectors, etc.). Paybacks for the ICS system are several years (16%) shorter than the commercial drainbacks (based on initial cost). Based on this comparison, the ICS is more attractive and would be the system of choice if paybacks were the criteria. Additionally, there may be opportunities for reducing the cost of ICS systems that will substantially improve their economic competitiveness compared with currently available commercial ICS systems. Figures 6-1 through 6-3 compare drainback and ICS current system economics for Phoenix, Denver, and Madison. Discounted paybacks versus current electricity costs and escalation rates for 5, 10, and 20 years are also plotted in each figure.

The drainback system that we analyzed contained a currently available off-the-shelf, low-cost collector that is also low performance. What impact would development of a low-cost, high-performance collector (e.g., a Brookhaven type high-temperature thin-film plastic) have on payback? If we use the same cost as for the low-cost collector but assume performance equivalent to that of the Novan collector used in the commercial drainback system, the payback would be shown by the open diamond in Figures 6-1 through 6-3. Thus the paybacks (based on initial cost) would drop as follows: Phoenix--10.3 to 9.0 yr, Denver--12.1 to 8.9 yr, Madison--13.5 to 10.0 yr. The impact of a high-performance, low-cost collector is especially significant in the colder climates where paybacks are reduced by about 25% compared to currently available low-cost, low-performance collectors.

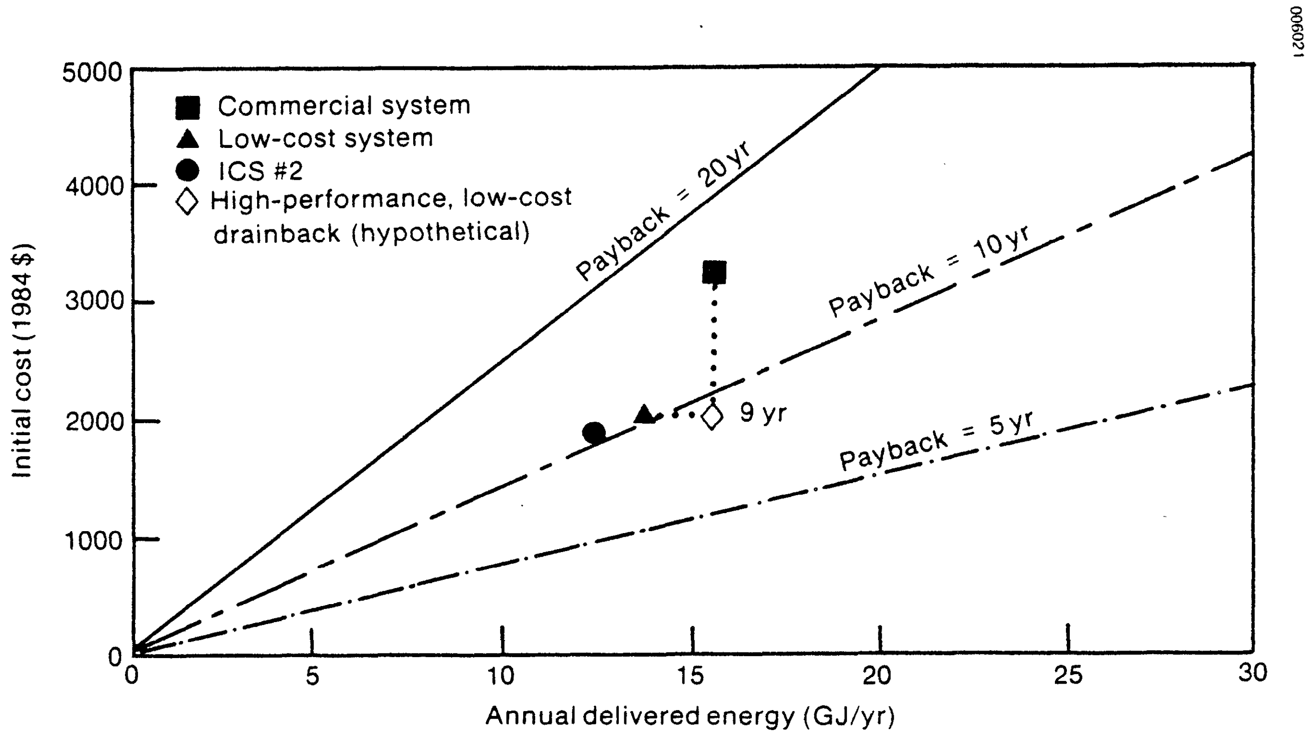

Figure 6-1. Discounted Payback against Electricity for Commercial Drainback, Low-Cost Drainback, and ICS #2 in Phoenix (discount rate = 10%, electrical fuel escalation rate = 7%)

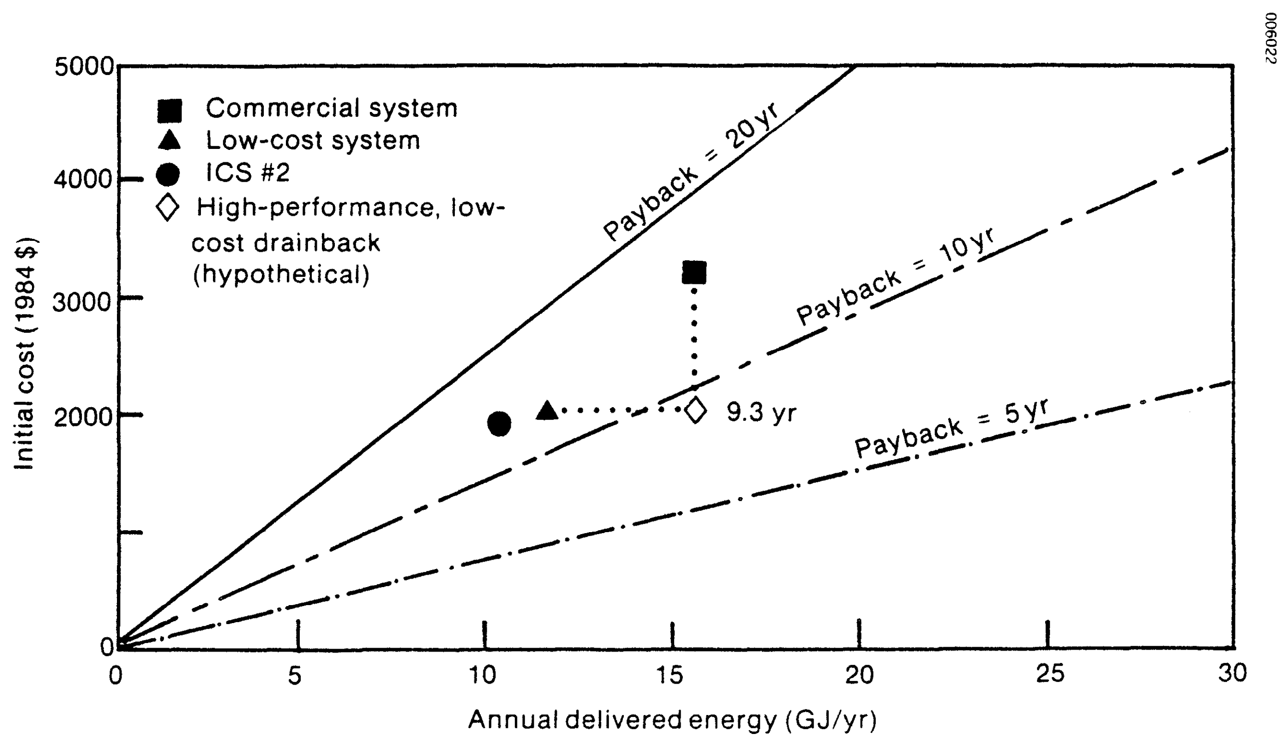

Figure 6-2. Discounted Payback against Electricity for Commercial Drainback, Low-Cost Drainback, and ICS #2 in Denver (discount rate = 10%, electrical fuel escalation rate = 7%)

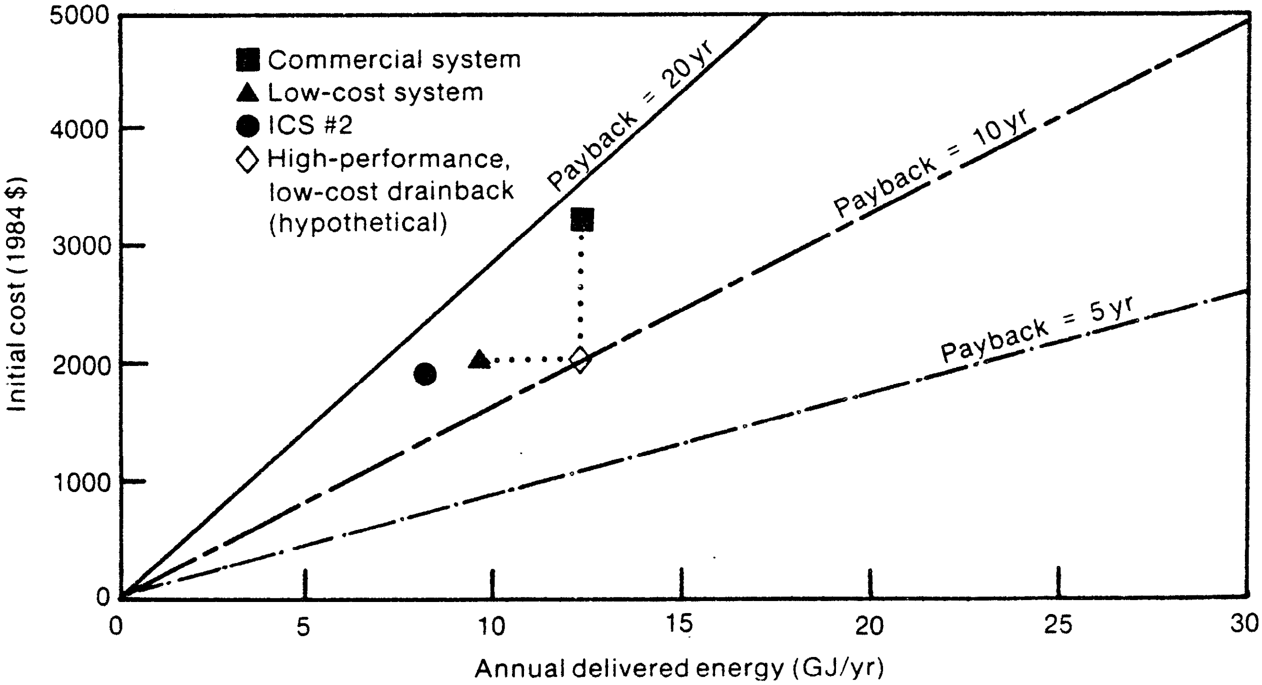

Figure 6-3. Discounted Payback against Electricity for Commercial Drainback, Low-Cost Drainback, and ICS #2 in Madison (discount rate = 10%, electrical fuel escalation rate = 7%)

While development of a low-cost, high-performance collector that also exhibits long-term durability can help improve system economics, paybacks still considerably exceed the five-year value needed to obtain a 40% market penetration. It is also unlikely that balance-of-system and labor costs can be reduced any further than those assumed for the low-cost drainback system. However, payback periods on the order of ten years versus electricity (without tax credits) are still much better than those of most systems sold today, and low-cost drainback systems using plastic piping, unpressurized storage, and advanced low-cost collectors may well warrant further development and testing.

ICS systems show better paybacks than other system types currently being marketed and, if they can be reduced in cost and adequately protected from freezing, they may show even greater promise than drainback systems for achieving large market penetration. They will likely still be applicable to domestic water heating only, however.

SECTION 7.0

CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

Low-cost versions of drainback systems have the potential to reduce installed costs by almost 40% over optimistically priced commercially available systems. If a durable, low-cost, high-performance collector could be developed, payback periods of slightly under 10 years (versus electricity) are possible without tax credits. Further cost reductions would require the development of other innovative system concepts.

Integral collector/storage (ICS) systems were studied as an alternative to drainback systems for heating domestic water (but not for space heating). Their attraction lies in their simplicity; namely, no pump or controller is required, and the entire system comes in one package. Two basic ICS system designs were studied: a single tank with reflector and a multiple-tank configuration. Two computer models were developed. One simulates an SRCC-82 system test and allows for ICS model parameters to be determined from published SRCC test results. A second model takes these parameters and, using a methodology developed at the University of Wisconsin, predicts annual performance.

The ICS simulation results indicate that attempts to reduce overnight losses by lowering the loss coefficient can unfortunately be offset by even small corresponding reductions in optical efficiency. In comparing the two ICS system types (single versus multiple tank), the single-tank system has lower heat losses due to a smaller tank area, but a lower optical efficiency due to the presence of the reflector. In terms of annual performance, neither system design emerged as a clear winner, although additional concentration is possible with the single-tank design (at an added cost).

The optimum tank volume (system capacitance) was found to be dependent on draw profile. For a continuous draw, performance at any given aperture area is completely independent of tank volume. (If the energy balance equation for a constant draw is integrated over time, the storage mass appears only in the tank internal energy term, and this term can be considered negligible over long periods such as a month.) Draw profiles characterized by an average draw temperature less than the average tank temperature (e.g., night draw) benefit from larger tanks which have a smaller diurnal temperature variation. Conversely, a draw profile weighted to the daytime would do better with smaller tank sizes (although as with other active systems, if the tank is too small, collector efficiency suffers during nondraw conditions). A complete study of this issue was not attempted.

A survey of ICS manufacturers revealed that system costs per unit area are only slightly less than those of other active systems on the market. Compared with flat-plate collector costs per unit area, ICS units are considerably more expensive. While the overall cost for a typical ICS system may be less than for a typical drainback system (e.g., comparing the ICS to the commercial drainback), the ICS system does not deliver as much energy. An economic comparison showed that the ICS system has a shorter payback than the commercial drainback system and about the same payback as the low-cost drainback system. It must be pointed out that the low-cost drainback system has not been tested or commercially developed and that the costs estimated for the ICS system were taken from the optimistic end of the cost range from the manufacturers' survey.

If a high-performance, low-cost, flat-plate collector could be developed having a system cost similar to the low-cost system evaluated in this report, but having the performance of the commercial system, then the overall economics are improved considerably.

7.2 RECOMMENDATIONS

Based on the findings of our study, we can recommend several areas for further evaluation. These areas include cost reduction, design innovation, analysis, and validation. Cost and design improvements will clearly have an impact in the marketplace. Analysis and validation will improve the confidence we have in our ability to predict performance. Both of these general areas need to be addressed further. Since ICS systems are not alone in challenging typical active systems for the domestic hot water heating market, other systems should be studied in the same context as have the two in this report. Unitary thermosiphon systems appear to have many of the same advantages of ICS systems and seem to perform better. Both the single fluid phase and boiling fluid versions should be included in future comparisons.

Although our installed cost estimates for low-cost drainback systems indicate substantial cost-reduction potential, the components have not yet been fully developed. Since there appears to be a real benefit to reducing drainback system cost with low-cost components, an analysis that evaluates various design options, materials, and related reliabilities would be of value to the program. The benefits of packaging low-cost drainback system components should be investigated. A durable, low-cost, high-performance collector still needs to be developed.

Since reducing the cost of ICS systems will greatly affect the payback economics, some additional study of new materials, design innovations, and other potentially cost-reducing design changes need to be undertaken. Other low-cost ICS system designs may also be attractive from both a cost and performance standpoint. Alternatives to the ICS system should also be evaluated.

We have demonstrated an ability to model ICS systems, both for short-term performance and for long-term, annual performance. The short-term performance has been partially validated against the SRCC 200-82 test results, but the long-term performance methodology has been validated by the University of Wisconsin for only several weeks of experimental data. To increase our confidence in the ability of the simple modeling approach, more long-term experimental data are needed. These data may already exist, and, if so, they should be obtained. If not, a program to acquire the necessary data should be undertaken. Both the National Bureau of Standards and the Bonneville Power Administration are currently conducting experimental programs that could provide these much-needed data.

In addition to the system level performance and cost studies, component level tests can yield some valuable information. In the past, component tests or long-term operational testing of systems have resulted in data that cannot be obtained in any analytical study. Failure modes, component life, and O&M data are important in the overall understanding of any solar technology. We should not neglect this type of testing for ICS systems.

In summary, drainback systems employing high-performance, low-cost collectors and low-cost balance-of-system components could lower payback periods versus electricity (without tax credits) to about 10 years. ICS systems have payback periods similar to drainback systems. If costs of ICS units could be reduced below current levels, then a significant decrease in payback periods may also be possible. Cost reductions are necessary in both systems to achieve more acceptable paybacks without tax credits.

SECTION 8.0

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SECTION 9.0

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APPENDIX A

PROGRAM LISTINGS

APPENDIX A.1

SRCC 200-82 SIMULATION

```
$NOFLOATCALLS
$DEBUG

      PROGRAM SRCC1
*******************************************************************************
*                                                                             *
*  THIS PROGRAM SIMULATES THE SRCC 200-82 SOLAR ONLY AND PREHEAT SYSTEMS      *
*  TEST FOR AN ICS COLLECTOR.  THERE ARE 3 TESTS: A NET ENERGY DELIVERY       *
*  TEST, A RESERVE ENERGY TEST AND A HEAT LOSS TEST.  THE ICS MODEL IS        *
*  DESCRIBED IN THE SERI REPORT: SERI/RR-253-2694 BY LEWANDOWSKI, LEBOEUF,    *
*  AND KUTSCHER (SEE SECTION 4.2).                                            *
*                                                                             *
*******************************************************************************

      IMPLICIT REAL*8 (A-H,L-Z)
      INTEGER DAY,HR,HRD,MIN,MIND,SEC,SECD,DAYOLD,HROLD,OUT,DAT,WORK,N
      CHARACTER RUN,PRN
      DIMENSION QS(24),BETA(24),TDRAW(3),Z1(12)
      EQUIVALENCE (QNET,Z1(1)),  (QNETH,Z1(2)),  (FOLD,Z1(3)),
     1            (QND,Z1(4)),   (QLH,Z1(5)),    (QLD,Z1(6)),
     2            (QIH,Z1(7)),   (QID,Z1(8)),    (QRES,Z1(9)),
     3            (QDRAW,Z1(10)),(QSD,Z1(11)),   (QL,Z1(12))

*  COMMON BLOCKS TO PASS VALUES TO THE ICS SUBROUTINE

      COMMON /COLL/ ETAO,BO,MCP,UA,MDOT,CP
      COMMON /AMB/ QSOLAR,ANG,TA,TIN,QSINC
      COMMON /TEMPS/ TO,TON(20),TBAR,TTANK
      COMMON /ENERGY/ QDEL,QLOSS,QINT
      COMMON /STEP/ DT

**********************  DATA INITIALIZATION  **********************************

*  INPUT TEST TYPE

 5    WRITE(*,'(/,1X,''Enter system type: 0=Solar Only''/,20X,
     1                                  ''1=Solar Preheat : ''\)')
      READ(*,*) ITEST
      IF((ITEST.NE.0).AND.(ITEST.NE.1)) GOTO 5

*  OUTPUT DEVICE

      WRITE(*,'(/,1X,''Do you desire printer output?(Y/N): ''\)')
      READ(*,'(A)') PRN
      IF((PRN.EQ.'Y').OR.(PRN.EQ.'y')) THEN

         OUT=5

      ELSE

         OUT=0

      ENDIF
```

```
      DAT=6
      WORK=7

*  DETAILED OUTPUT + SUMMARY OR JUST SUMMARY

 6    WRITE(*,'(/,1X,''Output choices,''//,1X,
     1                ''      Summary only enter 0''/,1X,
     2                ''Hour-by-hour output enter 1: ''\)')
      READ(*,*,ERR=6) IPRNT

      IF((IPRNT.NE.1).AND.(IPRNT.NE.0)) GOTO 6

*  OPEN OUTPUT AND DATA FILES

      OPEN(OUT,FILE='LPT1:',STATUS='NEW')
      OPEN(DAT,FILE='DEFAULT.DAT',STATUS='OLD')
      OPEN(WORK,FILE='WORK.DAT',STATUS='OLD')

*  DEFAULT COLLECTOR PARAMETERS ON FIRST PASS THROUGH PROGRAM

      READ(DAT,*) MASS,U,ETAO,BO,AREA,N

*  TEST PARAMETERS

      CP=4180.0
      MFLOW=0.2
      TSET=48.89

*  AMBIENT PARAMETERS

      TA=22.0
      DATA QS/8*0.0,315.0,470.0,570.0,660.0,700.0,660.0,
     1        570.0,470.0,315.0,7*0.0/
      DATA BETA/8*0.0,60.0,45.0,30.0,15.0,0.0,15.0,30.0,45.0,60.0,
     1          7*0.0/


*  TIME STEPS

      DATA TSTEPD,TSTEPN,TSTEPDL,TSTEPL/2.0,3600.0,20.0,57600.0/

*  DRAW PARAMETERS

      DATA TDRAW/28800.0,43200.0,61200.0/

*  BEGIN LOOP FOR NEW PARAMETERS

 10   CONTINUE

      IF(ITEST.EQ.0) WRITE (*,900) MASS,U,ETAO,BO,AREA,N
      IF(ITEST.EQ.1) WRITE (*,901) MASS,U,ETAO,BO,AREA,N
```

```
      WRITE(*,*) 'Enter new values at prompt, any character if no change
     1 desired'

      WRITE(*,'(/,1X,''Mass, kg: ''\)')
      READ(*,*,ERR=20) MASS

 20   MCP=MASS*CP
      WRITE(*,'(/,1X,''U, W/Sq-m/C: ''\)')
      READ(*,*,ERR=30) U

 30   WRITE(*,'(/,1X,''Optical Efficiency: ''\)')
      READ(*,*,ERR=40) ETAO

 40   WRITE(*,'(/1X,''BO: ''\)')
      READ(*,*,ERR=50) BO

 50   WRITE(*,'(/,1X,''Area, Sq-m: ''\)')
      READ(*,*,ERR=60) AREA

 60   UA=U*AREA
      WRITE(*,'(/,1X,''Number of Nodes: ''\)')
      READ(*,*,ERR=70) N
      IF(N.GT.20) GOTO 60

 70   CONTINUE
      WRITE(*,*) ' '

*  DRAW FLAGS

      IDRAW=0
      IDEND=0
      IWARN=0
      IWPRN=0

*  SET ENERGY VALUES TO ZERO VIA EQUIVALENT ARRAY

      DO 80 I=1,11
 80   Z1(I)=0.0

*  TEST PARAMETERS

      TIN=22.0
      TO=22.0

      DO 90 I=1,N
 90   TON(I)=TO

*  TIME VALUES

      DAY=1
      HR=0
      MIN=0
      SEC=0
      TIME=0.0
```

```
*********************** START TEST SIMULATION *******************************

*  PRINT HEADINGS

      IF(IPRNT.EQ.1) WRITE(OUT,905) DAY

      DAYOLD=DAY
      HROLD=HR

*  CHECK FOR DRAW TIME

 100  IF((TIME.EQ.TDRAW(1)).OR.(TIME.EQ.TDRAW(2)).OR.(TIME.EQ.TDRAW(3))
     1   .OR.(IDRAW.EQ.1)) THEN
           MDOT=MFLOW
           DT=TSTEPD
           IDRAW=1
      ELSE
           MDOT=0.0
           DT=TSTEPN-FLOAT(IDEND*((60*MIN)+SEC))
      ENDIF

*  CALL ICS PERFORMANCE ROUTINE

      QSOLAR=QS(HR+1)*AREA
      ANG=BETA(HR+1)/57.29578
      CALL ICS(N)

*  CHECK FOR DRAW, ACCUMULATE QNET, AND CHECK FOR END OF DRAW

      IF(IDRAW.EQ.1) THEN

        IF(ITEST.EQ.1) THEN

           QNET=QNET+QDEL


C   IF THE ICS SYSTEM CAN DELIVER TEMPS GREATER THAN TSET THEN THE
C   QDRAW CALCULATION IS NO LONGER VALID.  THE VOLUME OF THE BACKUP
C   TANK AND ITS STRATIFICATION AND HEAT LOSS CHARACTERISTICS MUST
C   BE KNOWN BEFORE THE CALCULATION CAN BE MADE, OR A TEMPERING
C   VALVE MUST BE INSTALLED AND MODELLED.  IN THIS CASE, A WARNING
C   TO THE USER IS ALL THAT IS PRINTED.

           IF((TBAR.GT.TSET).AND.(IWARN.EQ.0)) THEN

              IF(IPRNT.EQ.1) WRITE(OUT,925)
              IWPRN=1

           ENDIF

           QDRAW=QDRAW+MDOT*CP*(TSET-TIN)*DT
           IDEND=0
           IWARN=1
```

```
      IF(QDRAW/1.0D3.GE.14100.0) THEN

         QL=QL+QDRAW
         QDRAW=0.0
         F=QNET/QL

         IDRAW=0
         IDEND=1
         IDREND=1
         IWARN=0

         HRD=HR
         MIND=MIN
         SECD=SEC

      ENDIF

   ELSEIF(ITEST.EQ.0) THEN

      QNET=QNET+QDEL
      QDRAW=QDRAW+QDEL
      IDEND=0

      IF((QDRAW/1.0D3.GE.14100.0).OR.(TO.LE.35.0)) THEN

         QDRAW=0
         F=QNET/42300.0
         IDRAW=0
         IDEND=1
         IDREND=1

         HRD=HR
         MIND=MIN
         SECD=SEC

      ENDIF

   ENDIF

ELSE

      IDEND=0

ENDIF
```

```
*   SUM HOURLY AND DAILY ENERGY VALUES

      QSH=QSH+QSINC
      QNETH=QNETH+QDEL
      QLH=QLH+QLOSS
      QIH=QIH+QINT
      QSD=QSD+QSINC
      QLD=QLD+QLOSS
      QID=QID+QINT

*   INCREMENT TO NEXT TIME, CALCULATE NEW DAY,HR,MIN,SEC

      TIME=TIME+DT
      TIME=DMOD(TIME,8.64D4)
      IF(TIME.EQ.0.0) DAY=DAY+1
      HR=MOD(IDINT(TIME/3600.0),24)
      MIN=MOD(IDINT(TIME/60.0),60)
      SEC=MOD(IDINT(TIME),60)

*   IF NEW HR PRINT & RESET HOURLY VALUES

      IF(HR.NE.HROLD) THEN

         IF(IPRNT.EQ.1) THEN

            IF(IDREND.EQ.1) THEN

               WRITE(OUT,910) HROLD,HR,QSH/1.0D3,
     1                        QNETH/1.0D3 ,QLH/1.0D3,QIH/1.0D3,
     2                        HRD,MIND,SECD

            ELSE

               WRITE(OUT,920) HROLD,HR,QSH/1.0D3,QNETH/1.0D3,
     1                        QLH/1.0D3,QIH/1.0D3

            ENDIF

         ENDIF

         IDREND=0
         HROLD=HR
         QSH=0.0
         QNETH=0.0
         QLH=0.0
         QIH=0.0
```

```
*  IF END OF DAY PRINT & RESET DAILY VALUES

          IF(DAY.NE.DAYOLD) THEN
               IF(IPRNT.EQ.1) THEN

                    WRITE(OUT,930) QSD/1.0D3,QNET/1.0D3,QLD/1.0D3,
     1                             QID/1.0D3
                    WRITE(OUT,905) DAY

               ENDIF

               DAYOLD=DAY
               QSD=0.0
               FOLD=F
               QL=0.0
               QNET=0.0
               QLD=0.0
               QID=0.0
          ENDIF
     ENDIF

*  CHECK FOR DAILY ENERGY CONVERGENCE.  IF CONVERGENCE HAS OCCURED
*  THEN PERFORM RESERVE AND HEAT LOSS TESTS

     IF((HR.GE.18).AND.(IDRAW.EQ.0)) THEN

          IF((F-FOLD)/F.LT.0.03) THEN
               IF(IPRNT.EQ.1) WRITE(OUT,940) QNET/1.0D3
               GOTO 200
          ENDIF
     ENDIF

*  GO BACK TO BEGINNING OF NEXT TIME STEP

          GOTO 100


***********************  RESERVE ENERGY TEST  ********************************

 200 QSOLAR=0.0
     ANG=0.0
     MDOT=MFLOW
     DT=TSTEPD
     TIME=0.0
     QDP=0.0
     IF(IPRNT.EQ.1) WRITE(OUT,945)

*  CALL ICS PERFORMANCE ROUTINE

 210 CALL ICS(N)
     TIME=TIME+DT
     MIN=MOD(IDINT(TIME/60.0),60)
     SEC=MOD(IDINT(TIME),60)
     QDP=QDP+QDEL
```

```
      IF (SEC.EQ.0) THEN

           IF(IPRNT.EQ.1) WRITE(OUT,950) MIN,SEC,QDP/1.0D3,TO
           QDP=0.0

      ENDIF

      QRES=QRES+QDEL

*   IF TANK TEMP > TIN BY 3 C PRINT RESERVE TEST RESULTS AND PERFORM
*   HEAT LOSS TEST, OTHERWISE INCREMENT RESERVE TEST DRAW

      IF((TBAR-TIN).GT.3.0) THEN
           GOTO 210
      ELSE
           IF(IPRNT.EQ.1) WRITE(OUT,960) QRES/1.0D3
      ENDIF

**************************  HEAT LOSS TEST ***********************************
*
*   NOTE THAT THIS IS REDUNDANT: L IS AN INPUT.  THIS TEST IS JUST FOR FUN

*   CHARGE THE SYSTEM WITH 60 C WATER.

      QSOLAR=0.0
      ANG=0.0
      MDOT=MFLOW
      TIN=60.0
      DT=TSTEPD

*   CALL ICS ROUTINE

 300  TOLD=TBAR
      CALL ICS(N)

*   IF TBAR VARIATION < 0.1 C THEN PROCEED WITH COOLDOWN, OTHERWISE
*   KEEP CHARGING.  WHEN N>1 TBAR DECREASES SLIGHTLY FOR THE FIRST FEW
*   TIMESTEPS, THUS MAKING THE SECOND TEST BELOW FALSE AND TERMINATING
*   THE CHARGE.  THE FIRST TEST HAS BEEN ADDED TO AVOID TERMINATING
*   TOO SOON.

      IF((TBAR.LT.30.0).OR.((TBAR-TOLD).GT.0.1)) GOTO 300

*   INITIALIZE COOLDOWN

      MDOT=0.0
      DT=TSTEPL
      TINIT=TO

*   CALL ICS ROUTINE

      CALL ICS(N)
      TFINAL=TO
```

```
*  CALCULATE LOSS COEFFICIENT

      L=MCP/TSTEPL*DLOG((TINIT-TA)/(TFINAL-TA))

      IF(IPRNT.EQ.1) WRITE(OUT,970) TINIT,TFINAL,L

*  SUMMARY OF TEST RESULTS

      IF(ITEST.EQ.0) THEN

         WRITE(OUT,900) MASS,U,ETAO,BO,AREA,N
         WRITE(OUT,980) QNET/1.0D3,QRES/1.0D3,L

      ELSEIF(ITEST.EQ.1) THEN

         WRITE(OUT,901) MASS,U,ETAO,BO,AREA,N

         IF(IWPRN.EQ.0) THEN

            WRITE(OUT,981) QNET/1.0D3,QRES/1.0D3,L

         ELSE

            WRITE(OUT,982) QNET/1.0D3,QRES/1.0D3,L

         ENDIF

      ENDIF

      WRITE(WORK,*) MASS,U,ETAO,BO,AREA,N

*  END OF PROGRAM AND FORMAT STATEMENTS

      WRITE(*,'(1X,''Another run?(Y/N): ''\)')
      READ(*,'(A)') RUN
      IF((RUN.EQ.'Y').OR.(RUN.EQ.'y')) GOTO 10

      CLOSE(OUT)
      CLOSE(WORK)
      CLOSE(DAT)

      STOP

 900  FORMAT(1H1,5(/),26X,'SRCC 200-82 Simulation'/31X,'Solar Only'
     1 //,' Collector Parameters'//,9X,'Mass = ',F6.0,' kg'/,
     2 12X,'U = ',F4.1,' W/Sq-m/C'/,4X,
     3 'Opt Effic = ',F4.2/,11X,'BO = ',F4.2/,9X,'Area =',F5.2,
     4 ' Sq-m'/,12X,'N = ',I2/)
```

```
901  FORMAT(1H1,5(/),26X,'SRCC 200-82 Simulation'/30X,'Solar Preheat'
    1 //,' Collector Parameters'//,9X,'Mass = ',F6.0,' kg'/,
    2 12X,'U = ',F4.1,' W/Sq-m/C'/,4X,
    3 'Opt Effic = ',F4.2/,11X,'BO = ',F4.2/,9X,'Area =',F5.2,
    4 ' Sq-m'/,12X,'N = ',I2/)

905  FORMAT(1H1,80('*')//,31X,'QNET Test'//,32X,
    1 ' Day ',I2//,4X,'Hour',8X,'QINC',5X,'QNET',6X,'QL',6X,
    2 'QINT'/,17X,'kJ',7X,'kJ',7X,'kJ',7X,'kJ',12X,'Draw Results'/)

910  FORMAT(1H ,I4,'-',I2,3X,4(2X,F7.0),'    End of Draw at ',
    1          I2,':',I2,':',I2)

920  FORMAT(1H ,I4,'-',I2,3X,4(2X,F7.0))

925  FORMAT(1H0,'************ WARNING: TBAR > TSET ***************'/,
    1             ' ** QNET MAY BE GREATER THAN 14100 KJ THIS DRAW **'/)

930  FORMAT(1H0,10X,4(3X,'_______')//,11X,4(2X,F7.0))

940  FORMAT(1H0,50X,'Convergence with previous day'//,51X,'QNET=',1X,
    1 F7.0,' kJ'//,80('*'))

945  FORMAT(1H1,80('*')//,25X,'Reserve Energy Test'//,12X,'Time',19X,
    1 'QDEL',18X,'TO'/,13X,'Min',20X,'kJ',20X,'C'/)

950  FORMAT(1H ,10X,I2,':',I2,17X,F6.1,17X,F4.1)

960  FORMAT(1H0,32X,'_______'//,25X,'QRES=',1X,F7.0,' kJ'//,80('*'))

970  FORMAT(1H1,80('*')//,29X,'Heat Loss Test'//,16X,'ICS Model',
    1 //,' TINIT, C',10X,F4.1,//,' TFINAL, C',9X,F4.1,
    2 //,' L, W/C',11X,F5.2,//,80('*'))

980  FORMAT(1H ,80('*'),/,20X,'Summary of Results - Solar Only'//,
    1 5X,'QNET= ',F7.0,' kJ'//,5X,'QRES= ',F7.0,' kJ'//,8X,'L= ',
    2 ,F6.2,' W/C'//,80('*'))

981  FORMAT(1H ,80('*'),/,18X,'Summary of Results - Solar Preheat'//,
    1 5X,'QNET= ',F7.0,' kJ'//,5X,'QRES= ',F7.0,' kJ'//,8X,'L= ',
    2 F6.2,' W/C'//,80('*'))

982  FORMAT(1H ,80('*'),/,18X,'Summary of Results - Solar Preheat'//,
    1 5X,'QNET= ',F7.0,' kJ  Warning: QNET may be too large'/,
    2 23X,'          TDEL > TSET for some time steps',//,
    3 5X,'QRES= ',F7.0,' kJ'//,8X,'L= ',F6.2,' W/C'//,80('*'))

     END
```

```
      SUBROUTINE ICS(N)

*****************************************************************************
*                                                                           *
*  THIS SUBROUTINE MODELS AN ICS SYSTEM USING AN ANALYSIS DESCRIBED IN      *
*  SECTION 4.2 OF SERI/RR-253-2594.  THE ANALYSIS ASSUMES A LUMPED SYSTEM   *
*  AND A FULLY MIXED STORAGE TANK DIVIDED INTO N NODES. THE ROUTINE         *
*  REQUIRES INPUT DATA WHICH IS PASSED THROUGH COMMON BLOCKS.  THE INPUT    *
*  DATA  INCLUDES COLLECTOR  PARAMETERS, SOLAR INCIDENT, AMBIENT TEMP,      *
*  FLOW RATE, AND INLET TEMP.  THE OUTPUT IS ALSO PASSED THROUGH COMMON     *
*  AND INCLUDES OUTLET AND AVERAGE TANK TEMP, AND  DELIVERED, LOST AND      *
*  INTERNAL ENERGIES.                                                       *
*                                                                           *
*****************************************************************************

      IMPLICIT REAL*8 (A-H,L-Z)
      INTEGER N
      DIMENSION TI(20),TBARN(20),QLOSSN(20),QINTN(20)

*  COMMON BLOCKS

      COMMON /COLL/ ETAO,BO,MCP,UA,MDOT,CP
      COMMON /AMB/ QSOLAR,ANG,TA,TIN,QSINC
      COMMON /TEMPS/ TO,TON(20),TBAR,TTANK
      COMMON /TEMPS1/ TOENDN(20)
      COMMON /ENERGY/ QDEL,QLOSS,QINT
      COMMON /STEP/ DT

*  CALCULATE SOLAR ABSORBED

      QABS=QSOLAR*ETAO*(1.0-BO*(1.0/DCOS(ANG)-1.0))

      DO 10 I=1,N

*  CALCULATE CONSTANTS FROM DIFF EQTN SOLUTION

      IF(I.EQ.1) THEN

           TI(I)=TIN

      ELSE

           TI(I)=TBARN(I-1)

      ENDIF

      BETA=((QABS/N)+MDOT*CP*TI(I)+(UA/N)*TA)/(MCP/N)
      GAMMA=(MDOT*CP+(UA/N))/(MCP/N)

      C1=BETA/GAMMA
      X1=GAMMA*DT
      EX1=DEXP(-X1)
```

```
*  CALCULATE AVERAGE AND END OF TIME STEP TEMPERATURES

      TBARN(I)=C1-(TON(I)-C1)*(EX1-1.0)/X1
      TOENDN(I)=C1+(TON(I)-C1)*EX1

      QINTN(I)=MCP/N*(TOENDN(I)-TON(I))
      QLOSSN(I)=UA/N*(TBARN(I)-TA)*DT

 10   CONTINUE

*  CALCULATE ENERGY FLOWS IN JOULES

      QSINC=QSOLAR*DT
      QDEL=MDOT*CP*(TBARN(N)-TIN)*DT

      QLOSS=0.0
      QINT=0.0

      DO 20 I=1,N

           QLOSS=QLOSS+QLOSSN(I)
           QINT=QINT+QINTN(I)

 20   CONTINUE

*  RESET TEMPS FOR NEXT TIME STEP

      DO 30 I=1,N
 30   TON(I)=TOENDN(I)

*  SET AVERAGE AND END OF TIME STEP OUTLET TEMPS TO THOSE FOR NODE N

      TBAR=TBARN(N)
      TO=TON(N)

*  CALCULATE TANK TEMP AS AVERAGE OF AVERAGE NODE TEMPS

      TT=0.0
      DO 40 I=1,N
 40   TT=TT+TBARN(I)

      TTANK=TT/N

*  END OF ROUTINE

      RETURN
      END
```

APPENDIX A.2

ANNUAL PERFORMANCE
(UNIVERSITY OF WISCONSIN METHODOLOGY)

```
$NOFLOATCALLS
$DEBUG

      PROGRAM ZOLLICS

************************************************************************
*                                                                      *
*  THIS PROGRAM COMPUTES THE MONTHLY AVERAGE DRAW TEMPERATURE AND      *
*  SOLAR FRACTION OF AN ICS SYSTEM  OPERATING IN DENVER, PHOENIX,      *
*  OR MADISON  USING THE CORRELATION TO TRNSYS SIMULATIONS DEVELOPED   *
*  BY ALAN ZOLLNER AT THE UNIV. OF WISCONSIN.                          *
*                                                                      *
*  THE REFERENCE DOCUMENT FOR THIS METHODOLOGY IS ZOLLNER'S            *
*  THESIS:                                                             *
*                                                                      *
*         "A PERFORMANCE PREDICTION METHODOLOGY FOR INTEGRAL           *
*         COLLECTOR STORAGE SOLAR DOMESTIC HOT WATER SYSTEMS"          *
*                                                                      *
*         UNIVERSITY OF WISCONSIN-MADISON, 1984                        *
*                                                                      *
*                                                                      *
*  THE PROGRAM CANNOT TAKE CARE OF CHECKING FOR A REASONABLE           *
*  COMBINATION OF VOLUME, AREA, LOSS COEFFICIENT AND LOAD.  THE        *
*  USER IS WARNED THAT HE/SHE/IT MUST INPUT REALISTIC VALUES FOR       *
*  ICS PARAMETERS.  NOTE THAT THE PROGRAM DOES CHECK FOR VALUES        *
*  WHICH ARE OUT OF BOUNDS OF THOSE STUDIED BY ZOLLNER.  IT WILL,      *
*  HOWEVER, PROCEED WITH THE CALCULATIONS AFTER ISSUING A WARNING      *
*                                                                      *
************************************************************************

      REAL NUMER,NDAYS,MCP
      CHARACTER*10 CITY(3)

      DIMENSION TAMB(12), HTINP(13), HRMON(12),NDAYS(12),
     1TMAINS(12),TDRAW(12),SOLFRC(12),QDEL(12),HT(12)
     2,HTL(13,3),TMA(12,3),TAM(12,3),QLOAD(12)

*  SET DEFAULT VALUES FOR THE APERTURE AREA, THE LOSS
*  COEFFICIENT, THE DAILY DRAW MASS, AND TAU-ALPHA

      DRAWLIT = 300.

*  OPEN DATA INPUT FILE WITH INITIAL PARAMETERS

      OPEN(1,FILE='WORK.DAT',STATUS='OLD')
      READ(1,*) DMASS,ULOSS,TAUALFA,BO,APAREA,NODES

*  CONSTANT VALUES

      DATA CITY/'Denver','Phoenix','Madison'/
```

```
*  THESE SOLAR RADIATION VALUES ARE FOR APERTURE PLANE TILTED AT
*  LATITUDE ANGLE ONLY.  TO BE MORE GENERAL THIS COULD BE MODIFIED
*  TO GENERATE TILTED VALUES FROM HORIZONTAL VALUES, AS DOES FCHART

      DATA HTL/.52,.53,.66,.66,.69,.70,.72,.71,.67,.64,.50,.48,7.48,
     1          .54,.58,.74,.81,.86,.82,.78,.78,.75,.71,.58,.52,8.48,
     1          .33,.39,.49,.49,.57,.58,.61,.59,.51,.45,.29,.26,5.57/

      DATA HRMON /744.,672.,744.,720.,744.,720.,744.,744.,720.,
     1    744.,720.,744./

      DATA NDAYS /31.,28.,31.,30.,31.,30.,31.,31.,30.,31.,30.,31./

      DATA TMA/3.9,4.4,6.1,9.4,12.8,15.6,17.2,17.8,17.2,13.3,7.2,2.8,
     1          8.9,8.9,10.,11.1,13.9,15.,17.2,23.9,26.1,20.6,15.,12.2,
     1          12*7.2/

      DATA CPWAT /4.19/

      DATA TAM/0.,0.,3.,9.,14.,19.,23.,22.,17.,11.,4.,0.,
     1      10.7,12.8,15.4,19.8,24.6,29.2,32.9,31.7,28.8,22.3,15.4,11.4,
     1      -8.4,-6.5,-1.0,7.4,13.3,18.8,21.2,20.4,15.4,9.9,1.5,-5.6/

      DATA TSET /50./

*   PRINTED OUTPUT?

 1    WRITE(*,'(/,1X,''Do you want printed output(Y/N?): ''\)')
      READ(*,'(A)') IPRINT
      IF((IPRINT.EQ.'y').OR.(IPRINT.EQ.'Y')) THEN

         LUN=5

      ELSE

         LUN=0

      ENDIF

      OPEN(LUN,FILE='LPT1:',STATUS='NEW')

******    INPUT ANY CHANGES DESIRED IN THE DEFAULTS    *******
*
*         A WARNING IS ISSUED IF PARAMETER VALUES ARE
*         OUTSIDE THE RANGE OF TRNSYS RUNS MADE BY ZOLLNER.

 10   CONTINUE

 100  WRITE(*,900) DMASS,APAREA,ULOSS,DRAWLIT,TAUALFA,NODES

      WRITE(*,'(/,1X,''Enter new value at prompt or''/1X,
     1                 ''any character if no change desired'')')
```

```
      WRITE(*,'(/,1X,''Volume of ICS tank, liters: ''\)')
      READ(*,*,ERR=150) DMASS

 150  IF((DMASS.GT.250.0).OR.(DMASS.LT.130.0)) WRITE(*,800)

      WRITE(*,'(/,1X,''Aperture area  Sq. meters: ''\)')
      READ(*,*,ERR=200) APAREA

 200  DCHK=DMASS/APAREA
      IF((DCHK.GT.90.9).OR.(DCHK.LT.47.27)) WRITE(*,800)

      WRITE(*,'(/,1X,''Loss Coefficient, W/m2-Deg C: ''\)')
      READ(*,*,ERR=250) ULOSS

 250  IF((ULOSS.GT.4.44).OR.(ULOSS.LT.1.94)) WRITE(*,800)

      WRITE(*,'(/,1X,''Daily average hot water usage, liters/day: ''\)')
      READ(*,*,ERR=300) DRAWLIT

 300  WRITE(*,'(/,1X,''Optical efficiency: ''\)')
      READ(*,*,ERR=350) TAUALFA

 350  IF((TAUALFA.GT.0.69).OR.(TAUALFA.LT.0.39)) WRITE(*,800)

      WRITE(*,'(/,1X,''# of nodes: ''\)')
      READ(*,*,ERR=400) NODES

 400  CONTINUE

*  THIS CORRELATION FROM A SERI CURVE FIT TO FIG 3.21
*  OF ZOLLNER'S THESIS TO ACCOUNT FOR STRATIFICATION

      A=.32645*(1.0-EXP(-.7355*(NODES-1)))
      TT=DRAWLIT/DMASS

 475  WRITE(*,'(/1X,''City # (Note: there is no default)''/5X,
     1        '' Denver=1,Phoenix=2,Madison=3: ''\)')
      READ(*,*) ICITY
      IF((ICITY.NE.1).AND.(ICITY.NE.2).AND.(ICITY.NE.3)) GOTO 475

*  SET THE RADIATION, AMBIENT TEMP, AND MAINS TEMP
*  FOR THE CHOSEN CITY NUMBER

      DO 25 I=1,12

         TAMB(I) = TAM(I,ICITY)
         TMAINS(I) = TMA(I,ICITY)
         HTINP(I) = HTL(I,ICITY)

   25 CONTINUE

      HTINP(13) = HTL(13,ICITY)
```

```
*   COMPUTE THE MONTHLY DRAW MASS

      DRAWMAS = DRAWLIT

******************************************************************

*   BEGIN THE LOOP TO COMPUTE THE MONTHLY AVG. DRAW TEMPS
*
******************************************************************

      DO 600 M=1,12

*   CONVERT RADIATION TO PROPER UNITS

         HT(M) = HTINP(M) * 1000000.

*   COMPUTE MCP FOR SOLAR FRACTION CALCULATION

         MCP = CPWAT * DRAWMAS * NDAYS(M)

*   CALCULATE EACH TERM IN THE NUMERATOR

*   CONVERT ALL TEMPERATURES TO DEGREES KELVIN
*   ACCOUNT FOR THE EFFECTIVE SKY TEMPERATURE IN
*   COMPUTING THE AMBIENT TEMPERATURE

         TMAINK = TMAINS(M) + 273.
C        TAMBK = TAMB(M) + 273. - 3.

*   DENVER

         IF(ICITY.EQ.1) THEN

         TAMBK = TAMB(M) + 273. - 4.5

*   PHOENIX

      ELSE IF(ICITY.EQ.2) THEN

         TAMBK = TAMB(M) + 273. - 5.0

*   MADISON

      ELSE

         TAMBK = TAMB(M) + 273. - 3.0

      ENDIF

      T1 = HT(M) * APAREA * TAUALFA
      T2 = MCP * TMAINK
      T3 = ULOSS * APAREA * HRMON(M) * TAMBK * 3.6
```

```
*  COMPUTE THE NUMERATOR

      NUMER = T1 + T2 + T3

*  CALCULATE EACH TERM IN THE DENOMINATOR

      D1 = MCP
      D2 = ULOSS * APAREA * HRMON(M) * 3.6

*  COMPUTE THE DENOMINATOR

      DENOM = D1 + D2

*  CALCULATE THE AVERAGE DRAW TEMPERATURE FOR THE MONTH

      TDRAW(M) = (NUMER/DENOM) - 273.

*  CALCULATE QDEL AND QLOAD,THE ENERGY COLLECTED AND REQUIRED

      QDEL(M) = (MCP * (TDRAW(M) - TMAINS(M)))/1000.
      QLOAD(M) = (MCP * (TSET - TMAINS(M)))/1000.

*  CALCULATE THE MONTHLY SOLAR FRACTION

*  IF STRATIFIED, THEN USE THE CORRELATION TO TANK TURNOVER
*  OTHERWISE A=0

         SOLFRA = QDEL(M) / QLOAD(M)
         SOLFRC(M) = SOLFRA *(1.+(A*(1.-SOLFRA)/TT))
         QDEL(M) = SOLFRC(M) * QLOAD(M)

  600 CONTINUE

*  BEGIN LOOP TO PRINT THE RESULTS

      IF((IPRINT.EQ.'y').OR.(IPRINT.EQ.'Y')) THEN

        WRITE(LUN,900) DMASS,APAREA,ULOSS,DRAWLIT,TAUALFA,NODES

      ENDIF

      IF(NODES.GT.1) THEN

         WRITE(LUN,905) TT

      ELSE

         WRITE(LUN,'(/1X,''The tank is fully mixed'')')

      ENDIF

      WRITE(LUN,910) CITY(ICITY)
```

```
      TAMSUM=0.
      TMNSUM=0.
      TDRSUM=0.
      SFRSUM=0.
      QDLSUM=0.
      QLDSUM=0.

      DO 700 I=1,12

*  CONVERT INCIDENT RADIATION TO MEGAJOULES

         HTMJ = HTINP(I) * 1000. * APAREA

         WRITE(LUN,920) I,TAMB(I),TMAINS(I),TDRAW(I),HTMJ,
     1                 SOLFRC(I),QDEL(I)

*  SUM THE PERFORMANCE PARAMETERS FOR AVERAGING AND TOTALS

         TAMSUM = TAMB(I) * REAL(NDAYS(I))  + TAMSUM
         TMNSUM = TMAINS(I) * REAL(NDAYS(I)) + TMNSUM
         TDRSUM = TDRAW(I) * REAL(NDAYS(I)) + TDRSUM
         SFRSUM = SOLFRC(I) + SFRSUM
         QDLSUM = QDEL(I) + QDLSUM
         QLDSUM = QLOAD(I) + QLDSUM

  700 CONTINUE

*  COMPUTE THE AVERAGES

      TAMAVG = TAMSUM/365.
      TMNAVG = TMNSUM/365.
      TDRAVG = TDRSUM/365.
      QINAVG = HTINP(13) * 1000. * APAREA / 12.
      SFRAVG = QDLSUM/QLDSUM
      QDLAVG = QDLSUM/12.

*  COMPUTE THE ENERGY DELIVERED PER UNIT AREA

      QDAREA = QDLSUM/APAREA

*  COMPUTE THE TOTALS

      QINTOT = HTINP(13) * 1000. * APAREA
      QDLTOT = QDLSUM

*  PRINT OUT THE AVERAGES AND THE TOTALS

      WRITE(LUN,930) TAMAVG,TMNAVG,TDRAVG,QINAVG,SFRAVG,QDLAVG
     1,QINTOT,QDLTOT

      WRITE(LUN,940) QDAREA
```

```
*  END OF PROGRAM AND FORMAT STATEMENTS

      WRITE(*,'(/'' Another run?(Y/N): ''\')
      READ(*,'(A)') RUN
      IF((RUN.EQ.'Y').OR.(RUN.EQ.'y')) GOTO 10

      REWIND 1
      WRITE(1,*) DMASS,ULOSS,TAUALFA,BO,APAREA,NODES
      CLOSE(1)

      STOP

 800  FORMAT(/' WARNING: Parameter out of range of TRNSYS correlations')
 900  FORMAT (1H1,' ICS Parameters',//,5X,
     1   'Volume = ',F6.1,1X,'liters',/,5X,
     2   'Aperture area = ',F5.2,1X,'Sq. m',/,5X,
     3   'Loss Coefficient = ',F6.2,1X,'W/m2-Deg C',/,5X,
     4   'Daily hot water draw = ',F9.1,1X,'liters/day',/,5X,
     5   'Optical Efficiency = ',F4.2,/,5X,'# Nodes = ',I2)
 905  FORMAT(/,' The tank is stratified, with TT = ',F5.2)
 910  FORMAT(/,1X,A10,' (Note that solar radiation values are for',/,
     1   14X,'apertures tilted at latitude angle only)'//
     2   2X,'Month',2X,'Amb Temp',2X,'Main Temp',2X,
     3   'Draw Temp',2X,'Qinc, Tilt',2X,'Solar',4X,'Qdel',/,
     4   11X,'(C)',8X,'(C)',8X,'(C)',8X,'(MJ)',5X,'Fract',4X,'(MJ)'/)
 920  FORMAT(I5,5X,F5.1,7X,F4.1,7X,F4.1,4X,F7.0,
     15X,F4.2,3X,F7.0)
 930  FORMAT(1X,70('-')/,1X,'Averages',2X,F4.1,7X,F4.1,4X,
     1F7.1,4X,F7.0,2X,F7.2,3X,F7.0,/,1X,'Totals',34X,
     2F7.0,12X,F7.0)
 940  FORMAT(60X,F7.0,1X,'MJ/m2')


      END
```

APPENDIX B

MANUFACTURERS' SURVEY FORM

ICS MANUFACTURER SURVEY

Company:

Phone:

Contact:

Product: Date:

MARKETING

1. What is your marketing strategy(direct, wholesalers, etc.)?
2. Where is your product marketed?
3. Have you experienced any freeze related problems?
4. If you have a freeze related warranty, what are its terms and conditions?

DESIGN

1. How did you arrive at your current design?
2. What design improvements do you contemplate?
3. Can you send product literature?
4. Where has your product been tested?

COSTS

1. Can you give us your cost figures for:

    Manufacturing?

    Wholesaler/dealer?

    Installed system?

2. Without tax credits how would your marketing and costs be affected?

MISCELLANEOUS COMMENTS

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16. Abstract (Limit: 200 words) This report describes work performed in FY 1984 at the Solar Energy Research Institute as part of the continuing effort to lower the delivered energy cost of solar domestic hot water and space heating systems. In this work, a cost and performance comparison of drainback and integral collector storage (ICS) systems was conducted. Cost data for installed system costs were developed for both systems. Performance for the systems was generated using either accepted design tools (FCHART for drainback systems) or new methodologies (for the ICS systems). The cost and performance data were used to calculate discounted payback as a means for comparing the two systems and for assessing their market potential. The results of this economic analysis show that ICS systems have lower discounted paybacks than commercially available drainback systems. Low-cost drainback systems using new, low-cost components have about the same discounted payback as ICS systems.

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